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Techno-Economic Analysis of Integrated Power Generation and Desalination Systems

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Techno-Economic Analysis of Integrated Power Generation and Desalination Systems

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Dedicated to mom, dad, Erich, and Christopher.

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Techno-Economic Analysis of Integrated Power Generation and Desalination Systems

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Demand for energy and water are increasing worldwide, contributing to concerns about climate change and water scarcity. These concerns have motivated a wide range of research on the "energy-water nexus," i.e., the ways by which energy and water systems interact with each other. One strategy for dealing with water scarcity is to desalinate seawater or brackish groundwater. Because desalination is more energy intensive than conventional water treatment, it puts additional stress on energy systems and efforts to reduce carbon emissions. Thus, managing water scarcity requires a holistic approach to evaluating water and energy systems.

This manuscript presents two studies on energy-water systems that focus on electric power generation and desalination. The first study is a grid-level analysis of power generation and desalination systems in Kuwait with the goal of identifying strategies for reducing the cost and emissions. The second

of study is a systems level analysis of a reverse osmosis (RO) desalination plant integrated with a combined cycle natural gas plant using the Texas electricity and gas market as a case study.

The first study uses a unit-commitment model to simulate the operation of power generation and desalination plants in Kuwait. The model is used to evaluate the optimal allocation of fuel among Kuwait's power and desalination plants, the effect of building solar PV and new RO capacity in Kuwait, and the effect of implementing a tax on CO_2 emissions in Kuwait. These analyses find that any of these strategies could be effective at reducing emissions of CO_2, SO_2, and NO_x in Kuwait while also reducing costs or incurring a modest increase in cost.

The second study uses a mixed integer program to model the operation of an RO plant integrated with a small-scale combined cycle natural gas plant (CCGT) where the power plant can either power the RO plant or sell electricity to the grid. This facility is compared against a standalone RO plant to determine if the economic and environmental benefits of an on-site power plant outweigh its higher capital costs. These analyses indicate that a small-scale CCGT plant could share intake infrastructure with the RO plant, would have lower emissions than electricity from the grid, and that the levelized cost of water for an integrated CCGT-RO plant would be lower than a standalone RO plant.

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Glossary

Acronyms

MGD Million gallons per day

LNG Liquefied natural gas

DNG Domestic Natural Gas

HO Heavy Fuel Oil

GO Gas oil

CO Crude oil

RO Reverse osmosis desalination plant

ST Steam turbine

CCGT Combined cycle natural gas turbine power plant

LCOW Levelized cost of water [$\$/m^3$]

ERCOT Electric reliability council of Texas

TCM/d Thousand cubic meters per day

IWPP Independent water and power project

MSF Multiple stage flash

MED Multiple effect distillation

DEEP Desalination economic evaluation program

HHV Higher heating value

OCC Overnight capital cost

DAM Day-ahead market for electricity sales

EIA Energy Information Administration

CF Capacity factor

CRF Capital recovery factor

DT Plant down time [hr]

Chapter 2 Symbols

FC Fuel cost [USD]

VC Variable cost [USD]

EC Emissions cost [USD]

$\boldsymbol{Q}$ Hourly plant fuel consumption [MWh_{th}]

$\boldsymbol{P}$ Monthly fuel cost [USD/MWh$_{th}$]

$\boldsymbol{W_{thermal}}$ Hourly generation from thermal power plants [MWh]

$\boldsymbol{V_{desal}}$ Hourly desalination volume [MMGal]

$\boldsymbol{W_{aux}}$ Hourly auxiliary electricity consumption [MWh]

$\boldsymbol{W_{desal}}$ Hourly electricity consumption at desalination plants [MWh]

$\boldsymbol{W_{demand}}$ Hourly consumer demand for electricity [MWh]

$\boldsymbol{W_{pv}}$ Hourly generation from solar PV [MWh]

$\boldsymbol{a_0}$ Minimum hourly auxiliary electricity consumption [MWh]

$\boldsymbol{a_1}$ Linear coefficient for auxiliary electricity consumption [MWh/MWh]

$\boldsymbol{d_0}$ Minimum hourly electricity consumption at desalination plants [MWh]

$\boldsymbol{d_1}$ Linear coefficient for desalination plant electricity consumption [MWh/MMGal]

$\boldsymbol{c_1}$ Linear coefficient for fuel consumption associated with electricity generation [MWh$_{th}$/MWh$_e$]

$\boldsymbol{c_2}$ Linear coefficient for fuel consumption associated with desalination volume [MWh$_{th}$/MMGal]

$\boldsymbol{x_{gen}}$ Binary coefficient for power generation

$\boldsymbol{W_{thermal,max}}$ Max hourly electricity generation [MWh]

$\dot{\boldsymbol{W}}_{\boldsymbol{gen,cap}}$ Plant generating capacity [MW]

$\boldsymbol{x_{des}}$ Binary coefficient for desalination

$\boldsymbol{V_{desal,max}}$ Max hourly desalination volume [MMGal]

$\dot{\boldsymbol{V}}_{\boldsymbol{des,cap}}$ Desalination plant capacity [MGD]

$\boldsymbol{W_{pv}}$ Hourly generation from solar PV [MWh]

$\boldsymbol{Q_{rad}}$ Hourly solar irradiation [W/m^2]

$\boldsymbol{C_{pv}}$ Capacity of solar PV [MW]

$\boldsymbol{P_{pv}}$ Price of new solar PV [USD/MW]

$\boldsymbol{n_{ro}}$ Number of new RO plants

$\boldsymbol{C_{ro}}$ Capacity of new RO plants [MGD]

$\boldsymbol{P_{ro}}$ Price of new RO plants [USD/MGD]

$\boldsymbol{\phi_{CO_2}}$ CO_2 intensity of fuel consumption [ton/MWth]

ET Emissions tax [USD/ton]

Chapter 3 Symbols

$\boldsymbol{\eta}$ Power plant efficiency [MWe/MWth]

$\dot{\boldsymbol{W}}_{\boldsymbol{max}}$ Max power plant capacity [MW]

$\boldsymbol{V_{RO}}$ Desalination plant output [TCM]

$\dot{\boldsymbol{V}}_{\boldsymbol{RO,max}}$ Maximum desalination plant output [TCM/hr]

$\dot{\boldsymbol{V}}_{\boldsymbol{in}}$ Maximum seawater intake flow rate [TCM/hr]

$\boldsymbol{E_{RO}}$ Specific energy consumption of desalination [kWh/m^3]

$\boldsymbol{C_{RO}}$ Unit cost of reverse osmosis desalination [\$/m^3]

CI Carbon intensity [kg/MWe]

$\boldsymbol{C_{power}}$ Cost of powering the desalination plant [\$/m^3]

$\boldsymbol{W_{RO}}$ Energy consumption by the desalination plant [MWh]

$\boldsymbol{P_{elec}}$ Cost/price of electricity [\$/MWh]

$\boldsymbol{P_{ng}}$ Price of natural gas [\$/MWth]

$\boldsymbol{W_{gen}}$ Electrical energy generated by the CCGT plant [MWh]

$\boldsymbol{V_{O\&M}}$ Variable operation and maintenance cost of the power plant [\$/MWh]

$\boldsymbol{R_{elec}}$ Revenue from electricity sales [\$]

$\boldsymbol{W_{sell}}$ Electricity sold to the grid [MWh]

$\boldsymbol{x_{RO}}$ On/off variable for the desalination plant

$\boldsymbol{C_{cap}}$ Levelized capital cost for integrated power generation and desalination plants [$/m^3]

$\boldsymbol{F_{O\&M}}$ Fixed operation and maintenance cost for the power plant [$/kW-yr]

T Number of hours in a year

Chapter 1

Introduction

1.1 Motivation

Global demand for both water and electricity is increasing, contributing to concerns about climate change and water scarcity [6,7]. These concerns have motivated a wide range of research on the "energy-water nexus," i.e., the ways by which energy and water systems interact with each other. One strategy for dealing with water scarcity is to desalinate seawater or brackish groundwater. Because desalination is more energy intensive than conventional water treatment, however, it puts additional stress on energy systems and efforts to reduce carbon emissions [8–10]. Thus, managing water scarcity requires a holistic approach to evaluating water and energy systems.

Regions all over the world, including the Middle East, East Asia, and parts of the U.S., are increasingly reliant on desalination to augment water supplies. Global desalination capacity increased from 29 million cubic meters per day to over 92 million cubic meters per day from 2000 to 2017 [11]. Almost all global desalination capacity falls into two categories – thermal distillation, either multiple stage flash (MSF) or multiple effect distillation (MED), and reverse osmosis (RO). Until 2000, thermal distillation made up the majority of desalination capacity worldwide [11]. Global thermal distillation capacity is concentrated in energy rich Middle Eastern countries such as Saudi Arabia, Kuwait, and United Arab Emirates [12]. The specifics of thermal distillation vary by technology, but for both MSF and MED, a heat source, generally steam, is used to evaporate saline water, separating pure water vapor from concentrated brine. Until the 1990s, thermal distillation was the preferred technology for new desalination capacity because of it's simplicity and cost compared to RO. Since then, the cost and energy intensity for RO has decreased to the point that it has become the preferred technology for most new desalination capacity [11]. Instead of thermal energy, RO uses mechanical energy to push saline water through a semi-permeable membrane, resulting in separate streams of pure water and concentrated brine.

Desalination systems are often integrated with power plants to improve output or reduce costs, and the degree of integration varies by facility. An integrated power and desalination plant concept commonly found in oil-producing Middle Eastern countries like Saudi Arabia and Kuwait involves a cogeneration plant where either a Rankine cycle or combined cycle power plant is integrated with an MSF distillation plant. In this kind of integrated system, steam from the low pressure section of the steam turbine is used as the heat source for an MSF plant [13]. With this kind of arrangement, the distillation plant can only run if the power plant is also running. This constraint has significant implications for the electricity systems in countries like Kuwait. During periods with low electricity demand, cogeneration plants often have to run at low power output so that they can continue distilling water, and more efficient combined cycle power plants are operated sparingly or turned off entirely. This dynamic also makes it more challenging to integrate renewables into the power grid because they may have to be curtailed in favor of cogeneration plants. Reliance on cogeneration plants to produce electricity and water results in higher fossil fuel consumption and, therefore, higher costs and emissions. One of the objectives of this research is to investigate strategies for countries like Kuwait to reduce their energy consumption, costs, and emissions. The strategies considered in this analysis include investing in solar PV and new RO capacity, implementing taxes on CO_2 emissions, and restricting fuel consumption from certain facilities to reduce local emissions.

Another common way in which desalination plants can be integrated with power plants is for an RO plant to share intake and outfall infrastructure with and run off electricity generated by a co-located power plant. This arrangement can be found throughout the world, including the Tuaspring Reverse Osmosis desalination plant in Singapore and the Tampa Bay Seawater Desalination plant [14, 15]. These RO plants are integrated with large-scale power plants with generating capacities of hundreds of mega-watts or more. An RO plant only consumes a small percentage of the total generating capacity of such a large power plant, often less than the power plant's minimum output. For many of these integrated facilities, the RO plant was integrated with a pre-existing power plant, but the cost effectiveness of building a new large power plant to integrate with an RO plant depends local demand for new generating capacity. An RO plant might also be built with a small-scale power plant that is sized to serve the capacity of the RO plant. Another motivation of this research is to determine whether the energy savings and revenues from electricity sales are sufficient to justify the capital cost associated integrating an RO plant with a small-scale power plant. The analysis also evaluates the environmental benefits for an RO plant running of a small-scale power plant rather than purchasing electricity from the power grid.

1.2 Scope and organization

This manuscript has two analytical sections. The first of these sections includes an in-depth analysis of Kuwait's power generation and desalination systems that uses a unit-commitment framework to investigate different strategies for reducing the cost and environmental impact of these systems. The second section is a technical and environmental analysis of an RO plant integrated with a combined cycle power plant using the Texas market as a test bed. These analyses are followed by a summary and general conclusions.

The analysis of Kuwait's power generation and desalination systems is divided into seven sections. The first section describes the history of energy production, power generation, and desalination in Kuwait and reviews the relevant academic literature. The second section provides a mathematical description of the unit-commitment model used to analyze strategies for reducing the cost and environmental impact of power generation and desalination in Kuwait. The third section describes how the fuel availability constraints in the model are "calibrated" so that the model behaves realistically as compared the available historical data. The fourth section starts with an analysis of the allocation of fuels among the different power generation and desalination facilities in Kuwait as predicted by the model compared to the historical data. The analysis of the model output compared to the historical data is followed by a case study where the model is modified to limit the consumption of certain fuels from some of the power and desalination plants in Kuwait. The output of the original model is then compared to the output from the case study. The fifth section analyzes how adding solar PV and new RO capacity to Kuwait's existing power generation and desalination infrastructure effects power plant dispatch, fuel consumption, emissions, and system cost. Similarly, the sixth section analyzes how a carbon tax impacts fuel consumption, power plant dispatch, emissions, and system cost. The final section summarizes the results from the rest of the chapter and proposes future research.

The technical and economic analysis of a reverse osmosis desalination plant integrated with a combined cycle power plant in the Texas market is divided into five sections. The first section is a description of the potential benefits of integrating a desalination plant with a power plant and reviews the academic literature on integrated power generation and desalination plants. The second section describes the methods used for the technical and economic analyses including thermodynamic modeling software, data sources, and a mathematical formulation of an optimization model used to simulate the operation of an integrated power generation and desalination facility on the Texas power grid. The third section evaluates the results of the technical and economic analysis with and emphasizes the differences in capital and operating costs for an integrated power generation and desalination facility compared to a standalone desalination plant powered by electricity from the grid. The fourth and fifth sections summarizes the results and discusses how different modeling assumptions influenced the results and avenues for future research.

Chapter 2

Power Generation and Desalination Systems in Kuwait

2.1 Background

2.1.1 Energy-water Nexus in Kuwait

Kuwait is perhaps best known as a major oil producing country. Kuwait has more than 100 billion barrels of proven oil reserves and produces almost 3 million barrels of crude oil daily [16]. Despite its substantial natural resources, Kuwait did not become a significant energy producer until after World War II. Kuwait's Greater Burgan oil field, considered to be the second largest conventional field in the world behind Saudi Arabia's Ghawar field, was first discovered in 1938, but production did not begin until 1946 [17].

As Kuwait's oil production increased, the country started to invest in power generation and desalination capacity to provide electricity and water for its population. Kuwait's first desalination plant, an MED plant with a capacity of 2.4 million gallons per day (MGD), was completed in 1953 [13]. The first power plant was installed in Kuwait in 1958 with a capacity of 15 MW [18]. By 1965 Kuwait had a population of less than 500,000 people and a GDP per capita of less than 5000 in current USD [1].

Kuwait's population and GDP have grown substantially in recent decades, as shown in Figure 2.1. Kuwait's population and GDP increased by 144% and 321%, respectively, from 1995 to 2015. The increase in GDP is largely a result of increased oil production and record-setting oil prices over the same time period as shown in Figure 2.2 [2]. Kuwait's crude oil production increased by 36% from 1995 to 2015, and the annual average price of crude oil peaked at over 111 $/bbl in 2012. The sharp decline in oil prices starting in 2014 corresponds with the decrease in Kuwait's GDP the same year.

Increased population and wealth and access to cheap energy have resulted in sharp increases in demand for electricity and water. Demand for electricity and water in Kuwait increased by 186% and 144%, respectively, from 1995 and 2015 as shown in Figure 2.3 [3, 4]. Almost 99% of Kuwait's fresh water demand has been met through desalination in recent years. As of 2015, Kuwait has over 18 GW of installed power generation capacity and over 500 MGD of desalination capacity.

Most of Kuwait's desalination capacity is integrated with its power generation systems in the form of steam turbine cogeneration plants, where steam is extracted from the low pressure section of a turbine and used as a heat source for distillation as illustrated by Figure 2.4. Multiple stage flash (MSF) distillation units integrated with steam turbine cogeneration plants account for more than 450 million gallons per day (MGD) of desalination capacity, and electrically powered reverse osmosis (RO) desalination capacity account for another 60 MGD.

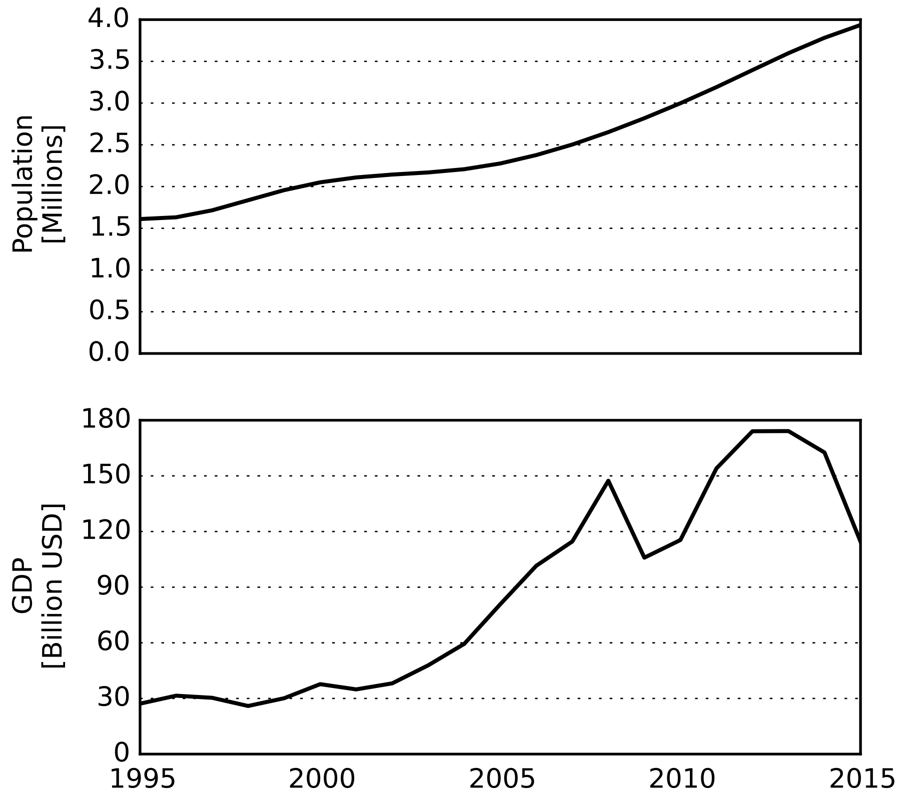

Figure 2.1: Kuwait's population and GDP increased by 144% and 321%, respectively, from 1995 to 2015 [1].

Increasing demand for electricity and water has resulted in higher demand for primary energy in the form of oil and gas derived fuels. All of Kuwait's utility-scale power generation assets, including steam turbine cogeneration plants, combined cycle gas turbine power plants, and open cycle gas turbines, use fossil fuel energy sources, including domestically produced natural gas (DNG), imported liquified natural gas (LNG), heavy fuel oil (HO), gas oil (GO), and crude oil (CO). Kuwait's increased demand for natural gas is of

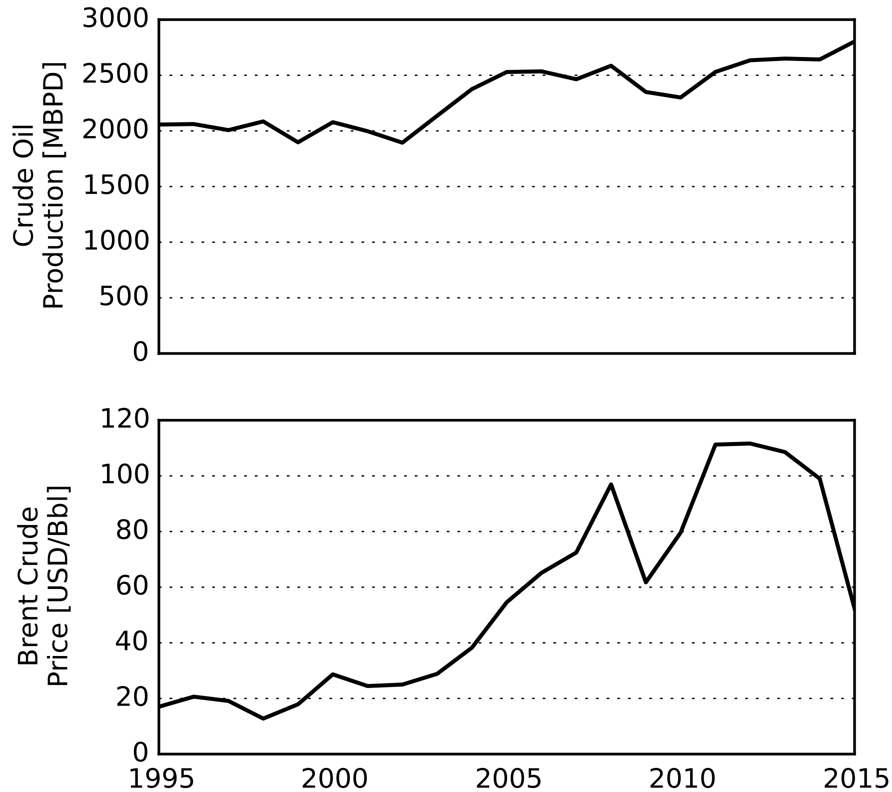

Figure 2.2: Kuwait's oil production increased by 36% from 1995 to 2015, over which time the price of crude oil peaked at over 111 \$/bbl [2].

particular concern. Despite being a major oil producing country, Kuwait has been a net importer of natural gas since 2009 as shown in Figure 2.5 [5].

In addition to importing LNG, Kuwait is also consuming more fuel oil for power generation as shown in Figure 2.6 [5]. Imported LNG and fuel oil are both more expensive than domestically produced natural gas, and Kuwait's energy costs have risen accordingly. As of 2013, Kuwait was spending as

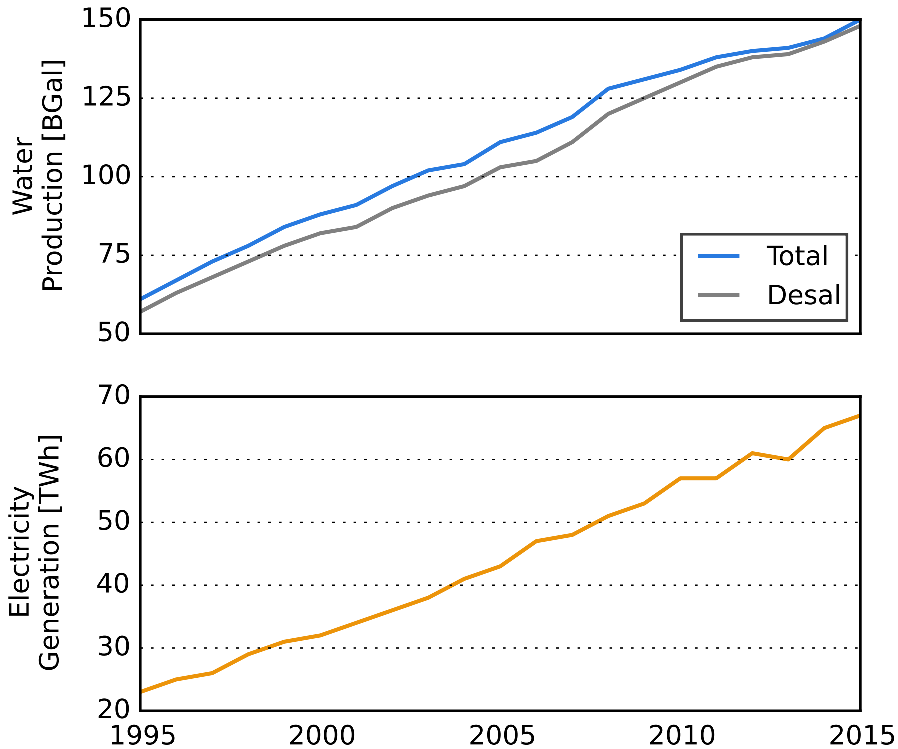

Figure 2.3: Demand for electricity and water has increased by 186% and 144%, respectively, from 1995 to 2015 [3, 4].

much as a third of its annual oil revenue on water and electricity production, a percentage that has likely increased after years of low oil prices [19]. As of 2015, Kuwait had the highest cost of generating electricity of any country in the Gulf Cooperation Council (GCC) [20]. In addition to being more expensive than domestically produced natural gas, using fuel oil for domestic power generation and desalination also cuts into potential revenues that can be earned from selling fuel oil on the global market [18].

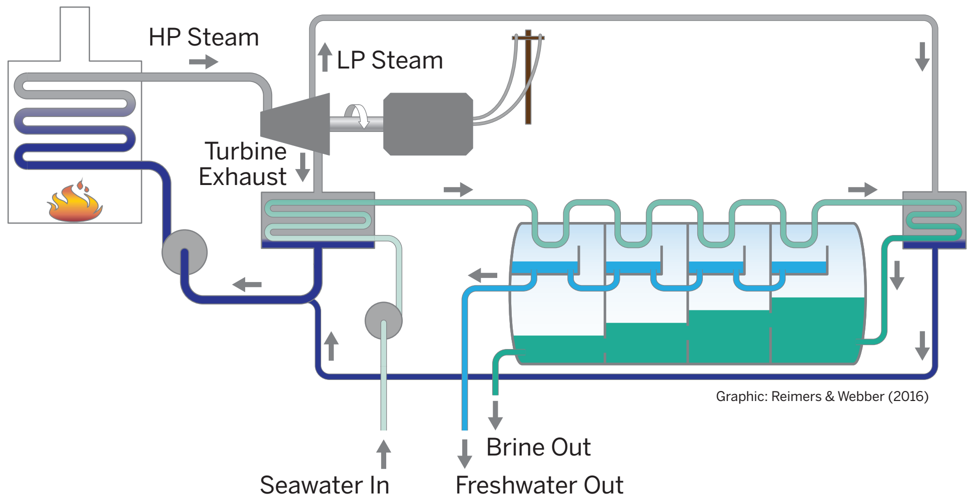

Figure 2.4: In a cogeneration power and desalination plant, steam is removed from the low pressure section of the turbine and used as the heat source for a distiller.

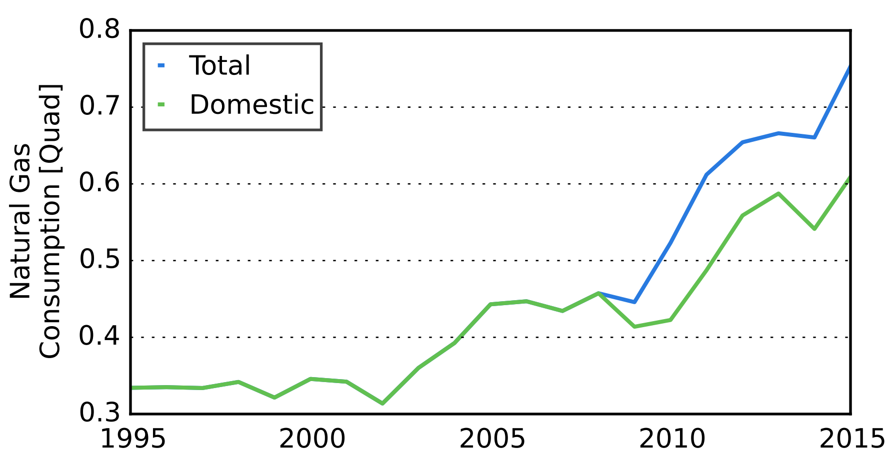

Figure 2.5: Despite being a major oil producing country, Kuwait has been a net importer of natural gas since 2009 [5].

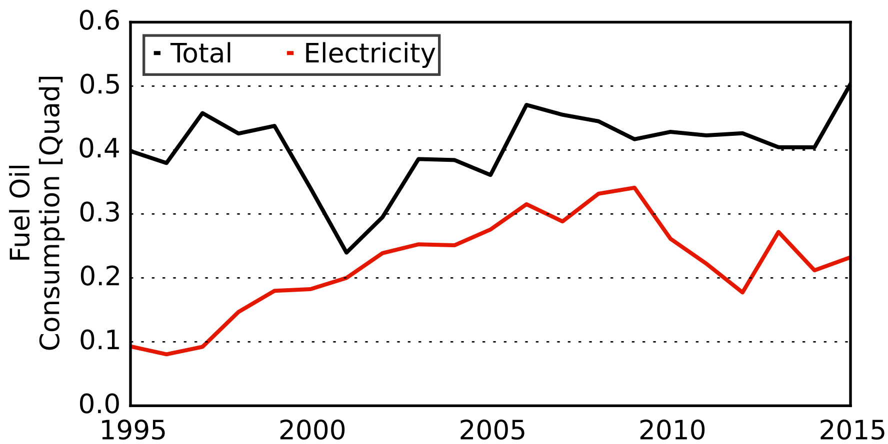

Figure 2.6: A significant percentage of Kuwait's fuel oil production is consumed for power generation and desalination [5].

Fuel oil is not only more expensive than natural gas, it also emits more CO_2, SO_2, and NO_x than natural gas per unit of energy, as shown in Figure 2.7. Kuwait ranks 172, 164, and 157 out of 180 countries for CO_2, SO_2, and NO_x emissions, respectively, according to the Environmental Protection Index [21].

In light of both economic and environmental concerns, Kuwait is seeking ways of reducing the cost and emissions associated with their power generation and desalination systems. This study includes a review of the existing literature on the energy-water nexus in Kuwait, the technical literature on fuel-flexible power systems integrated with water treatment systems, and strategies for countries similar to Kuwait to reduce energy consumption and emissions while meeting demand for electricity and water.

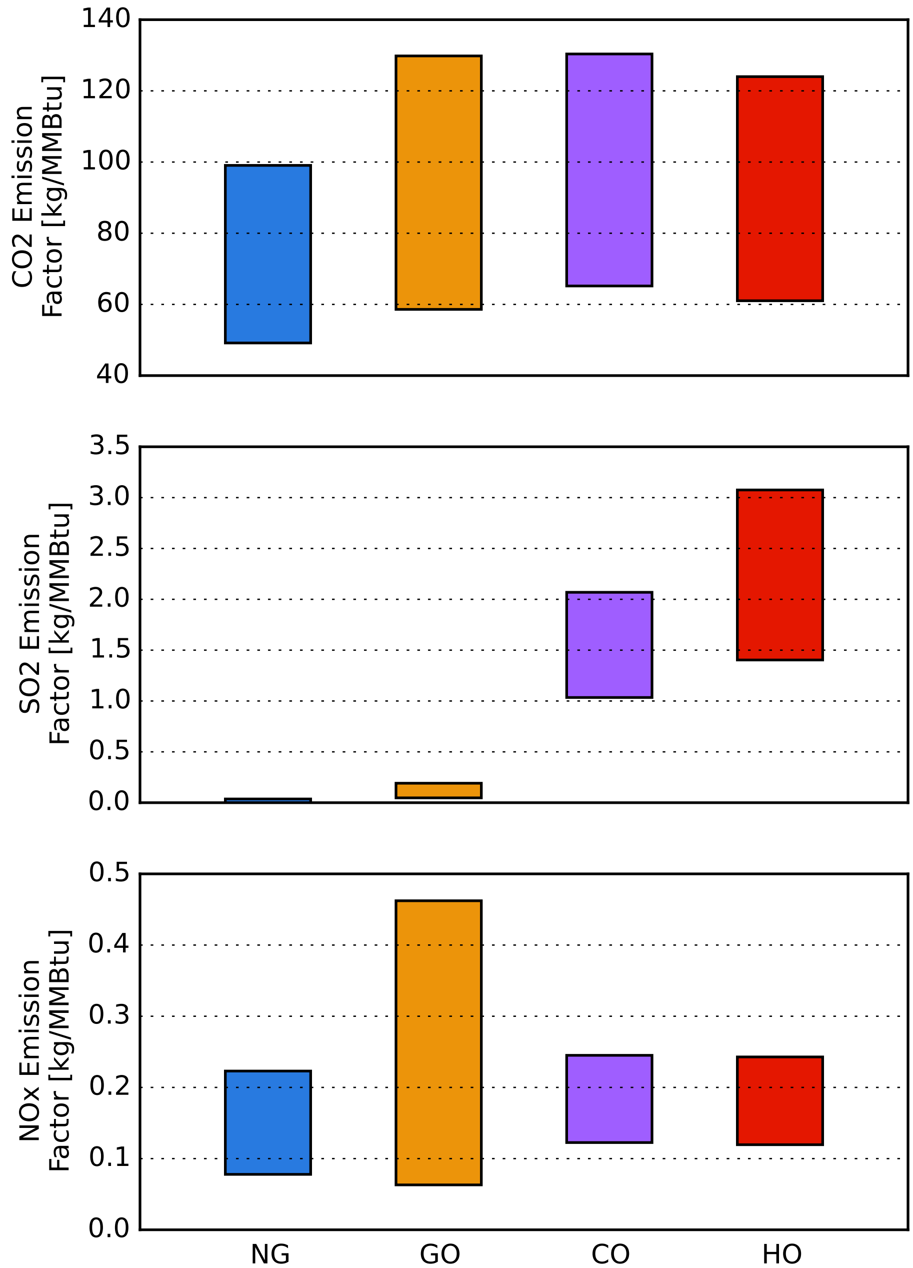

Figure 2.7: Emission factors for each fuel vary from month to month and are slightly different for steam turbine and gas turbine power plants.

2.1.2 Background Literature

There have been many studies that focus on the energy-water nexus in Kuwait and other GCC countries that are reliant on fossil fuels for energy and desalination for most of their water supply. In Kuwait, recent trends indicate that thermal distillation technologies like multiple stage flash will continue to be a significant component of Kuwait's desalination capacity for the next several decades [22]. As recently as 2011, a new 45 MGD distillation plant was integrated with a combined cycle power plant at the Shuaiba North complex [4].

There are numerous disadvantages to Kuwait's reliance on thermal distillation for producing freshwater. Compared to seawater RO, thermal distillation is more energy intensive, and thus more costly and environmentally impactful [23]. Thermal distillation also has a negative effect on the power system, because almost all of Kuwait's thermal distillation plants are integrated with steam turbine cogeneration plants. These cogeneration plants have to stay on-line to meet demand for desalinated water, even in periods with low electricity demand [24].

Because cogeneration plants have to run to desalinate water, they run at low capacity factors in periods with low electricity demand as shown in Figure 2.8. More efficient combined cycle power plants are either shut off or run at low capacity in periods with low electricity demand, also shown in Figure 2.8. Thus, relying on thermal distillation makes Kuwait's power systems more energy intensive for two reasons: 1) power plants are less efficient when they operate below full capacity, and 2) less efficient cogeneration plants are operated more often than more efficient combined cycle power plants.

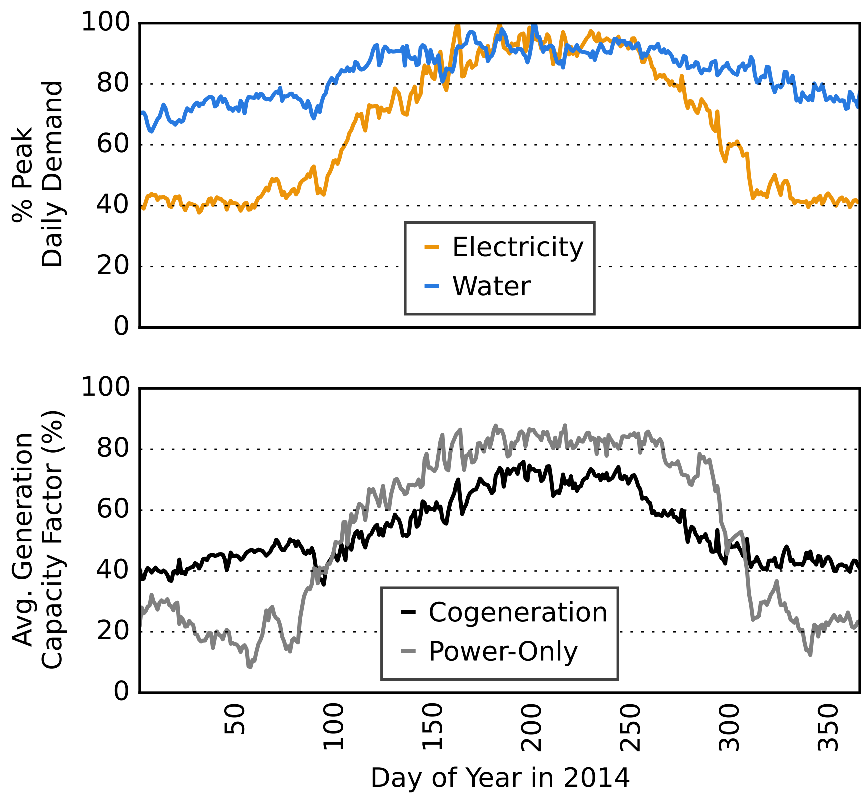

Figure 2.8: Because cogeneration plants need to stay turned on to distill water even in periods with low electricity demand, cogeneration plants and more efficient combined cycle power plants, i.e., "power-only" plants, run below full capacity for much of the year [3, 4].

Because relying thermal distillation technologies increases the energy intensity of both desalination and power generation systems, several studies have recommended that Kuwait invest in building more RO desalination capacity [19, 25]. Switching from thermal distillation to RO would reduce the energy intensity of desalination and allow efficient combined cycle power plants to be dispatched ahead of older, less efficient steam turbine plants on the power grid. Kuwait has already made some progress in this regard by investing in two 30 MGD RO plants in the last five years [4]. Even so, RO only accounts for just over 10% of Kuwait's desalination capacity.

By reducing the need to keep cogeneration plants running to distill water, new RO capacity would also allow Kuwait to integrate more renewable energy into the grid. There have been several studies that have evaluated Kuwait's renewable energy resources and how well the existing infrastructure and electricity markets could integrate renewable generation into their electric grid [20,26]. Solar power technologies in particular look regionally appropriate for Kuwait, which has some of the best solar potential in the world. Solar irradiation also coincides with much of the daytime electricity demand for air conditioning, the largest component of electricity demand in Kuwait [3]. There are some challenges associated with solar generation in Kuwait. For example, the extreme temperatures tend to reduce the efficiency of solar PV, and dust storms would increase O&M cost. Concentrated solar power (CSP) is more attractive in some respects because thermal energy can be stored and discharged after the sun sets. However, CSP has higher capital costs compared to solar PV and conventional generation technologies. Kuwait currently has modest plans for renewable energy development including a 50 MW CSP plant called the Shagaya Project and 10 MW each of wind and solar PV capacity

[27, 28].

Among the goals of this study is to systematically evaluate the economic and environmental effects of adding solar PV and new RO capacity to Kuwait's existing power generation and desalination infrastructure. This analysis is conducted using an economic dispatch framework, also called "unit-commitment," that models the performance of power generation and desalination assets in Kuwait and schedules their operation to meet demand for electricity and desalinated water with minimal system costs.

There is a large body of research on the use of unit commitment models for analyzing electric power systems [29, 30]. Unit commitment models are often applied to investigating the technical and economic impact of integrating intermittent renewables with existing electric grids [31, 32]. For example, unit-commitment models have been used to investigate how solar PV capacity can lead to periods with low net loads followed by steep ramp rates as solar generation goes offline before peak electricity demand (so-called "duck-curve" problems) [31, 33]. A related issue for both wind and solar is curtailment, i.e., when generation from intermittent resources exceeds net electricity demand, and so the solar generators' output has to be reduced or shut off [33]. The likelihood of curtailment increases as intermittent generation capacity increases [33]. A consequence of this dynamic is that without additional investment in transmission or electricity storage, there can be diminishing cost-effectiveness of investing in renewable energy capacity, thus limiting the extent to which renewable energy can be deployed to reduce the consumption of fossil fuels and associated emissions.

Unit commitment and economic dispatch models have also been used to consider many other concepts relevant to this analysis of Kuwait's power and desalination systems. For example, there have been several papers that include constraints on the availability of fuels [34–36]. Fuel supply may be constrained based on contracts with suppliers, pipeline flow dynamics, or extreme weather events. There have also been studies that seek to model power systems with "fuel flexible" generators, that is, generators that can burn a variety of fuels, as is the case in Kuwait [37, 38]. These fuel related analyses tend to focus more on computational methods for solving models with complicated fuel constraints as opposed to applying these models to real-world power systems. This manuscript builds upon these studies that incorporate fuel constraints and fuel-flexible generation into economic dispatch models by applying these concepts to Kuwait's power generation and desalination systems.

There have also been studies that use of unit commitment models to analyze power systems that are integrated with water treatment systems, as is the case in Kuwait. A series of papers from Santhosh et al. uses a unit commitment framework to investigate the operation of a power system that includes cogeneration power generation and desalination systems, power-only generators, and reverse osmosis desalination plants to meet demand for electricity and water [39, 40]. This analysis provides a template for modeling integrated power generation and desalination systems. This work builds upon and varies from Santhosh in a number important ways. Firstly, where Santhosh models demand for desalinated water on an hourly basis with a peak at midday, this manuscript models desalination demand on a daily basis so that the desalination plants can be "dispatched" around peak electricity demand. This modification is justifiable because Kuwait has billions of gallons of underground storage capacity [4]. Secondly, where Santhosh uses one day as a representative demand profile, this manuscript considers an entire years' worth of historical demand data so that seasonal differences in operation can be taken into account. Lastly, this manuscript includes a thorough investigation of how solar PV could be integrated into Kuwait's power system.

In Hickman et al., a unit-commitment framework was used to analyze the integration of renewable energy sources, solar PV in particular, into power systems that are tightly coupled with water treatment systems [41]. Hickman highlights the simultaneous benefits of solar PV in reducing primary energy consumption for power generation and desalination while also reducing water consumption for power generation. Hickman's work is particularly relevant to this manuscript because it uses Middle East inspired case studies in the analysis. This work adds to Hickman's work in several ways. Like Santhosh, Hickman's case studies only consider a twenty-four hour demand profiles instead of a full year. Hickman also scales solar to account for 20% of peak demand, where this manuscript considers the impact of adding a range of PV capacity to a system like Kuwait's that is heavily reliant on cogeneration plants to meet demand for desalinated water. Above a certain capacity of solar PV, curtailment can be expected to increase as solar PV is shut off in favor of cogeneration power plants. This work considers adding both solar PV and new RO capacity to a system like Kuwait's. New RO capacity can reduce demand on cogeneration plants for distilling water, and, thus, reduce the curtailment of solar PV.

Lastly, there have been studies that use unit-commitment models to investigate the effects of emission taxes on power plant dispatching and system emissions [42]. This manuscript investigates the impact of a range of CO_2 taxes on both power plant dispatch and optimal fuel consumption in Kuwait. It stands to reason that with a high enough tax on carbon emissions, the consumption of different fuels could change in favor of those with lower emission intensity. As in Nawaf et al., carbon taxes may also have an impact on emissions of other pollutants such as SO_2 and NO_x [42]. It will also be interesting to compare the difference in effects achieved by emissions taxes as opposed to investments in new power generation and desalination capacity.

In summary, this analysis builds upon the existing literature on unit-commitment models by combining and adding to many previously explored concepts using data specific to Kuwait's power and desalination systems. This model simultaneously optimizes the dispatch of power generation and desalination systems to meet demand for water and electricity at minimal cost. This model includes constraints for allocating fuels with limited availability among power and desalination plants. This model also also includes inputs for solar PV and new RO capacity and for taxes on CO_2 emissions. Unlike much of the existing literature, this analysis considers a simulation of an entire year of operation for Kuwait's power generation and desalination systems, rather than a representative twenty-four hour period. Another feature of this model not considered in the existing literature is the ability to restrict consumption of certain fuels at specific locations for the purpose of reducing local emissions of SO_2 and NO_x and investigating the effect of this fuel restriction on system-wide fuel consumption patterns. The following section contains a mathematical description of the model used for this analysis.

2.2 Methodology

Model Overview

This study features grid-level analyses of power generation and desalination systems in Kuwait using a unit-commitment dispatch model. The unit-commitment model was run for each day of 2014 to estimate the optimal dispatch schedule and resultant fuel consumption, cost, and emissions associated with power generation and desalination in Kuwait. In this model, thermal power plants and solar PV are used to power RO desalination plants and meet demand for electricity, and thermal distillation and RO plants were used to meet demand for desalinated water. A conceptual illustration of the model is shown in Figure 2.9.

The purpose of these analyses is to identify strategies for reducing the cost and emissions associated with power generation and desalination in Kuwait. The strategies considered in this study include optimally allocating fuels between power and desalination plants, investing in solar PV and new

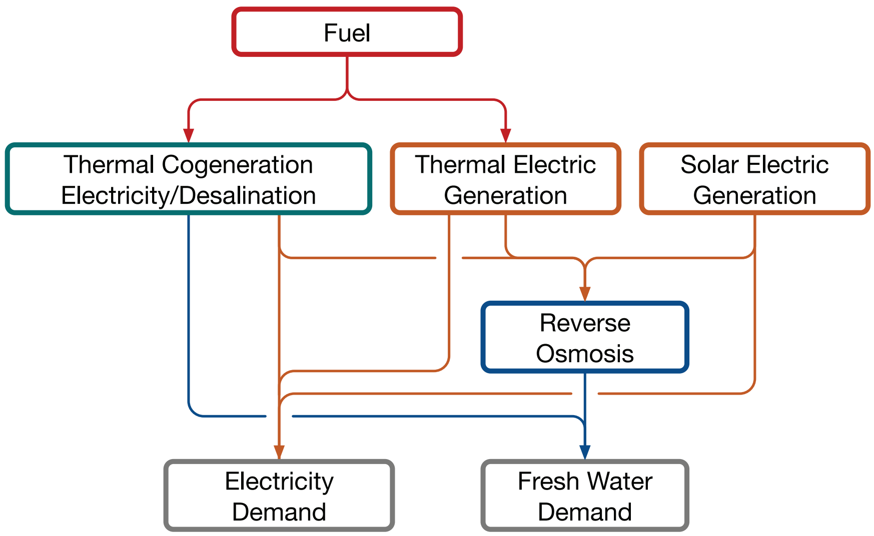

Figure 2.9: In this model of Kuwait's power generation and desalination systems, thermal power plants and solar PV are used to power RO desalination plants and meet demand for electricity, and thermal distillation and RO plants were used to meet demand for desalinated water.

RO capacity, and implementing a CO_2 emission tax on power generation and desalination plants in Kuwait. The first step in evaluating these strategies is to define a mathematical model that can approximate the operation of Kuwait's existing power generation and desalination systems. Kuwait's existing power generation and desalination facilities include cogeneration power and distillation plants where the power plant is either a Rankine cycle or a combined cycle, combined cycle and open cycle gas turbine power plants that only generate electricity, and RO desalination plants. A full list of abbreviations used for these facilities is shown in Table 2.1. Inputs to the model including regression coefficients, fuel prices, and electricity and water demand are based on data reported by Kuwait's Ministry of Electricity and Water.

Table 2.1: These abbreviations are used to refer to Kuwait's different power generation and desalination plants. Note that all of Kuwait's steam turbine power plants (ST) are cogeneration plants integrated with distillation plants. Also note that the abbreviations "EGT" and "NGT" are used to differentiate separate sets of CCGT plants at the Az-Zour South complex.

Az	*Az-Zour South*
DE	*Doha East*
DW	*Doha West*
Sb	*Sabiya*
SN	*Shuaiba North*
SS	*Shuaiba South*
Sw	*Shuwaikh*
ST	Steam turbine
CCGT	Combined cycle gas turbine
EGT	Emergency gas turbine
NGT	New gas turbines
GT	Open cycle gas turbine
RO	Reverse osmosis plant
MSF	Multiple Stage Flash

The objective of the model is to minimize the total operating cost, OC, for a set of generators, G, summed over an entire day, D. The operating cost is the sum of the the cost of fuel, FC, shown in equation 2.1, and the variable cost, VC, shown in equation 2.2.

$$FC = \sum_{f \in F} \sum_{g \in G} \sum_{t \in D} P(f,t) \times Q(f,g,t) \tag{2.1}$$

$$VC = \sum_{g \in G} \sum_{t \in D} VC_{power}(g) \times W_{thermal}(g,t) + VC_{desal}(g) \times V_{desal}(g,t) \tag{2.2}$$

$$OC = FC + VC \tag{2.3}$$

Where P is the monthly price for each fuel, Q is the hourly quantity of each fuel consumed by a generator, VC_{power} is the variable cost of each power plant, VC_{desal} is the variable cost of each desalination plant, $\mathrm{W}_{thermal}$ is the gross hourly electricity generation of each power plant, and V_{desal} is the hourly output of each desalination plant.

Constraints on the operation of the power generation and desalination systems include fuel and electricity consumption, minimum and maximum hourly output, and minimum up and down time[1]. There are also system-wide constraints governing the demand for electricity and desalinated water. The gross electricity produced by the set of thermal generators on an hourly basis has to account for the auxiliary power needed to run the power stations, W_{aux}, the electricity needed to run the desalination plants, W_{desal}, and the consumer demand for electricity, W_{demand}, as shown in equation 2.4.

$$\sum_{g \in G} W_{thermal}(g,t) = \sum_{g \in G} (W_{aux}(g,t) + W_{desal}(g,t)) + W_{demand}(t) \tag{2.4}$$

Where W_{aux} and W_{desal} are determined based on linear regressions as shown in equations 2.5 and 2.6:

$$W_{aux}(g,t) = a_0(g) + a_1 W_{thermal}(g,t) \tag{2.5}$$

$$W_{desal}(g,t) = d_0(g) + d_1(g) V_{desal}(g,t) \tag{2.6}$$

[1]Minimum up time refers to the minimum time a plant has to run before it can be shut off. Similarly, minimum down time refers to the minimum time a plant has to be shut off before it can be turned on.

Note that equation 2.6 refers to the electricity consumption for both thermal and reverse osmosis desalination plants. The sum of each plant's hourly desalination volume has to equal the daily demand for desalinated water as shown in equation 2.7.

$$\sum_{g \in G} \sum_{t \in D} V_{desal}(g,t) = \sum_{t \in D} V_{demand}(t) \tag{2.7}$$

The fuel consumption for all power and desalination plants is estimated using a multi-linear regression of the hourly gross electricity production and desalination volume as shown in equation 2.8. Note that for power-only plants, c_2 is always zero, and for RO plants, both c_1 and c_2 are always zero because RO plants only consume electricity.

$$Q(g,t) = c_1(g) W_{thermal}(g,t) + c_2(g) V_{desal}(g,t) \tag{2.8}$$

The maximum gross electricity generation for each thermal power plant, $W_{thermal,max}$, is limited by its generation capacity in MW, $\dot{W}_{gen,cap}$, as shown in equation 2.9.

$$W_{thermal,max}(g,t) \leq x_{gen}(g,t) \dot{W}_{gen,cap}(g) \tag{2.9}$$

Where x_{gen} is a binary on/off decision variable for each power plant. The minimum power output for the power plants is defined as 40% of the capacity of one of the subunits. For example, the $AzST$ cogeneration plant has eight steam turbines with a capacity of 300 MW each. Thus, the minimum power output for each $AzST$ subunit is 120 MW. The maximum hourly desalination volume for each desalination plant is limited by its desalination capacity, $\dot{V}_{des,cap}$, in million gallons per day (MGD) as shown in equation 2.10.

$$V_{desal,max} \leq \frac{1}{24}\frac{d}{hr}x_{des}(g,t)\dot{V}_{des,cap}(g) \tag{2.10}$$

Where x_{des} is a binary on/off decision variable for each desalination plant.

The minimum hourly desalination volume for each thermal plant is defined as half the capacity of one of the subunits. For example, the *DEST* cogeneration plant has seven distillation units with a capacity of 6 MGD each. Thus, the minimum hourly desalination volume for each distillation unit associated with *DEST* is 125 kGal. Similarly, the minimum hourly desalination volume for the RO plants is defined as 40% of the capacity of the RO plant. For example, each of the current RO plants in Kuwait has a capacity of 30 MGD. Thus, the minimum hourly desalination volume of these RO plants is 500 kGal. Lastly, the thermal distillation units are constrained such that they can only operate if the associated steam turbine power plant is operating, as shown in equation 2.11. Note that equation 2.11 only applies to cogeneration plants and is not applied to RO desalination plants.

$$x_{gen}(g,t) \geq x_{des}(g,t) \tag{2.11}$$

A summary of the number of subunits, regression coefficients, and generation and desalination capacity associated with each power plant is included in Table 2.2.

The model also includes minimum up and down time constraints for the power and desalination plants, that is, if a plant is turned off, it has to stay off

Table 2.2: These inputs are used to determine the electricity and fuel consumed by each subunit of the power and desalination plants and to limit their maximum and minimum hourly electricity and water output.

Plant	Subunits	a0	a1	c1	c2	d0	d1	GenCap	DesCap
AzST	8	4.547	0.065	2.33	354.55	0.418	23.89	300	14.4
DEST	7	2.738	0.05	3.02	245.02	0.122	22.25	150	6
DWST	2	4.668	0.063	1.97	363.01	1.618	19.84	300	12
	6	4.668	0.063	1.97	363.01	1.942	19.84	300	14.4
SbST	8	3.344	0.065	2.36	209.53	1.345	18.91	120	12.5
SSST	6	1.582	0.056	2.58	291.06	0.504	17.66	48	6
SwST	3	0	0	0	400.59	8.293	12.59	0	6.5
SNCCGT	1	3.663	0.026	2.93	89.91	4.625	23.64	875.5	45
AzEGT	1	0.551	0.028	2.39	0	0	0	680	0
	1	0.417	0.028	2.39	0	0	0	515	0
AzNGT	2	-1.182	0.021	2.64	0	0	0	800	0
SbCCGT	3	4.851	0.022	2.55	0	0	0	655.5	0
AzGT	4	0.111	0.003	4.10	0	0	0	27.7	0
DEGT	6	0.043	0.071	6.29	0	0	0	18	0
DWGT	5	0.022	0.016	2.84	0	0	0	28.2	0
SbGT	6	0.075	0.028	3.23	0	0	0	41.7	0
	4	0.112	0.028	3.23	0	0	0	62.5	0
SwGT	6	0.064	0.022	2.71	0	0	0	42	0
AzRO	1	0	0	0.00	0	2.531	16.55	0	30
SwRO	1	0	0	0.00	0	1.145	21.91	0	30

for at least a minimum amount of time and vice versa. The formulation of the minimum up and downtime constraints was taken from Carrion et al. and is shown in equations 3.11 and 3.12. [29]. Approximate values for the minimum up and down times for the power plants were taken from Kumar et al., and the minimum up and down time for all of the desalination plants is assumed to be four hours [43].

$$\sum_{n=k}^{k+DT-1} [1 - x_{plant}(n)] \geq DT[x_{RO}(k-1) - x_{plant}(k)] \qquad \forall k = 1 \cdots T - DT + 1 \tag{2.12}$$

$$\sum_{n=k}^{T}\{1 - x_{plant}(n) - [x_{RO}(k-1) - x_{plant}(k)]\} \geq 0 \qquad (2.13)$$
$$\forall k = T - DT + 2 \cdots T$$

Optimal Fuel Allocation

A novel feature of this model is that it has separate decision variables for the consumption of different fuels. Most of the power and desalination plants in Kuwait are fuel flexible and can consume a variety of fuels including domestically produced natural gas (DNG), imported liquified natural gas (LNG), heavy fuel oil (HO), crude oil (CO), and gas oil (GO). The monthly price in 2014 for fuels used by power and desalination plants in Kuwait is shown in Figure 2.10. The total hourly fuel consumption for each power and desalination plant is defined as the sum of each type of fuel consumed as shown in equation 2.14.

$$Q(g,t) = \sum_{f \in F} Q(f,g,t) \qquad (2.14)$$

In addition to the cost of different fuels, the availability of each fuel is a determining factor in how the model allocates fuels among the various power and desalination plants. A variety of data sources including fuel consumption data provided by the Kuwait Foundation for the Advancement of Science (KFAS), historical natural gas production data, and reported LNG import capacity are used to approximate the maximum availability of the various fuels as summarized in the **Fuel Availability Constraints** section below. Because

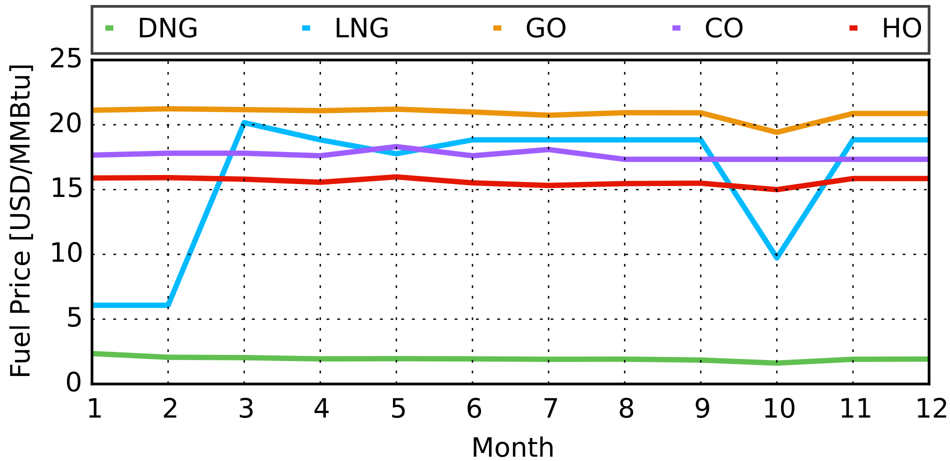

Figure 2.10: Monthly fuel prices for 2014 were used as inputs for the unit commitment dispatch model.

domestic natural gas is the cheapest fuel for power generation and desalination in Kuwait, it is always consumed according to its maximum daily availability.

Unfortunately, KFAS was unable to provide data on the fraction of domestically produced natural gas made available for power generation and desalination as opposed to other uses such as process heat or as a feedstock for other chemical products. Thus, this analysis includes a calibration step in which the fraction of domestic natural gas made available for power generation and desalination (DNGF) is incremented from 10–100% at 10% intervals. The output of the model is then compared against historical fuel consumption data to determine the value of DNGF with which the model output is most closely aligned with historical data. The sum of the absolute value differences in fuel consumption, shown in equation 2.15, is used to determine the value of DNGF used for this analysis.

$$min(\Sigma_{f \in F} Q(f)_{model} - Q(f)_{historical}) \rightarrow DNGF_{analysis} \tag{2.15}$$

Fuel Availability Constraints

The following list describes how the availability of domestic natural gas, liquified natural gas, heavy fuel oil, crude oil, and gas oil is constrained in the unit commitment model.

- Domestic natural gas

  The availability of domestically produced natural gas is estimated from two factors, 1) the historical production of natural gas, and 2) the fraction of domestically produced natural gas that is made available for electricity generation and desalination. For example, in 2014, Kuwait produced approximately 530 billion cubic feet of natural gas [44]. Thus, the daily production of natural gas was approximated for this work as a constant 1.5 million cubic feet. This model is calibrated by treating the percentage of domestically produced natural gas (DNGF) that is made available for electricity generation and desalination as an independent variable and incrementing it from 10-100%.

- Liquified natural gas

  The availability of LNG is based on the reported import capacity in Kuwait, approximately 760 million cubic feet per day [45].

- Heavy fuel oil

  Historical data on daily heavy fuel oil consumption are used to estimate the availability of heavy fuel oil. The sum of hourly fuel oil consumption for each day cannot exceed historical heavy fuel oil consumption on that day.

- Gas oil, crude oil

  The model does not include any constraints on the consumption of gas oil or crude oil. It does not seem reasonable that there should be any limits on the availability of crude oil in Kuwait. Gas oil is the most expensive fuel available, and so the model will tend to limit the use of gas oil in favor of other fuels.

Adding Solar PV and RO Capacity

Once the model has been calibrated, solar PV and RO capacity can be added to Kuwait's existing power generation and desalination assets in the model. The constraint on hourly electricity generation being sufficient to meet hourly demand can be modified to include generation from solar PV as shown in equation 2.16. This analysis considers the addition of 1, 2, 4, 8, 12, and 16 GW of solar PV respectively to Kuwait's 16 GW of thermal power generation.

$$\sum_{g \in G} W_{thermal}(g,t) + W_{pv}(t) = \sum_{g \in G} (W_{aux}(g,t) + W_{desal}(g,t)) + W_{demand}(t) \quad (2.16)$$

Where the hourly output from solar PV, W_{pv}, is limited by the solar radiation, Q_{rad}, and installed capacity of solar PV, C_{pv}, as shown in equation 2.17. Note that the 1/1000 m^2/W is included based on the standard definition of solar panel capacity.

$$W_{pv}(t) \leq {}^{1m^2}/_{1000W} \times Q_{rad}(t) \times C_{pv} \tag{2.17}$$

Without modifying any constraints, new RO plants can be added to the existing set of RO plants in the model. This analysis considers the addition of one, two, or three 30 MGD RO plants, each of which is assumed to have approximately the same energy intensity as the existing RO plants at the Shuwaikh and Az-Zour facilities. The analysis on new RO capacity differs from the analysis of new solar PV capacity in several ways. With solar PV capacity, the solar output was treated as a continuous variable between zero and the maximum output. With new RO plants, however, each new RO plant has its own variable for desalination volume in between minimum and maximum output, where turndown is assumed to be 40% of maximum output. These new RO plants also have minimum up and down time like the other desalination plants. The effect of these constraints is that each new RO plant can be dispatched separately.

After running the model for a whole year with the parameters associated with solar PV and new RO capacity, the annual cost of the system can be calculated including the annual financing cost of solar PV and new RO capacity as shown in equation 2.18.

$$AnnualCost = OC + cfr \times (P_{pv} \times C_{pv} + n_{ro} \times P_{ro} \times C_{ro}) \tag{2.18}$$

Where n_{ro} is the number of new RO plants and C_{ro} is the capacity of each new RO plant. The price of solar PV capacity, P_{pv}, is assumed to be 1200 \$/kW based on information from Lazard, and the overnight capital cost of new RO plants, P_{ro}, is assumed to be 4.28 million \$/MGD based on information from Global Water Intelligence's `desaldata.com` [11, 46].

Taxing CO_2 Emissions

The calculation of the operating cost defined in equation 2.3 can be modified to include taxes on CO_2 emissions, EC, as defined by equations 2.19 and 2.20.

$$EC = \sum_{f \in F} \sum_{g \in G} \sum_{t \in T} Q(f, g, t) \times \phi_{CO_2}(f) \times ET \tag{2.19}$$

$$OC = FC + VC + EC \tag{2.20}$$

Where ϕ_{CO_2} is the CO_2 emission intensity of each fuel as and ET is the emission tax rate. This analysis considers CO_2 taxes ranging from 10–100 \$/ton at \$10 increments.

2.3 Model Calibration

After defining the mathematical model, the model had to be calibrated to accurately simulate Kuwait's power generation and desalination systems. The model was calibrated by treating the fraction of domestic natural gas made available for power generation and desalination as an independent variable ranging from 10–100% of total natural gas production in Kuwait in 2014. The output of the model was then compared to the historical fuel consumption, and equation 2.15 was used to determine which value for the availability of domestic natural gas most closely matched the historical data. Figure 2.11 shows how the fuel consumption output by the model compares to historical data for natural gas, heavy fuel oil, crude oil, and gas oil. The two most noteworthy differences between the model and the historical data is a much higher consumption of crude oil and almost no consumption of gas oil.

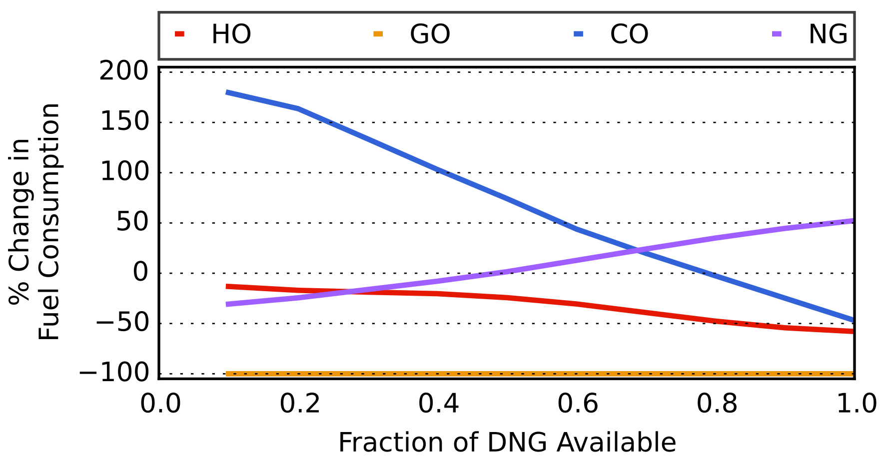

Figure 2.11: Compared to the historical data, the most noteworthy difference in the model output is higher crude oil consumption and almost no gas oil consumption.

The basis for the difference in gas oil consumption is straightforward. There is no limit on the consumption of either crude oil or gas oil in the model, but gas oil is the most expensive fuel for each month as shown in figure

2.2. There are a few possible explanations for the increased consumption of crude oil. For example, the constraint on the availability of heavy fuel oil may be too restrictive. This model uses the historical consumption data as the upper bound on the availability of heavy fuel oil. If less than 100% of the available heavy fuel oil is utilized, as is the case on days with low energy demand as shown in Figure 2.12, the leftover heavy fuel oil is not available to be consumed on subsequent days. In practice, heavy fuel oil could be purchased in advance and stored. Thus, more heavy fuel oil could be consumed on days with high energy demand, offsetting consumption of crude oil. Another possible explanation is that Kuwait favors burning gas oil instead of crude oil for power generation or desalination to reduce emissions of SO_2 and NO_x or because burning crude oil leads to higher O&M costs. Another possible explanation is the actual availability of crude oil for power generation and desalination is limited by the extent to which crude oil is committed to export contracts.

Equation 2.15 was used to determine which input for the availability of domestic natural gas most closely reproduces the historical fuel consumption. That result is plotted in Figure 2.13. This figure indicates that the difference between the model fuel consumption and the historical data is minimized when it is assumed that half of the natural gas produced in Kuwait is available for power generation and desalination. In addition to minimizing the sum of the difference for all fuels, the absolute difference in total natural gas consumption is also minimized with this constraint and is also shown on Figure 2.13.

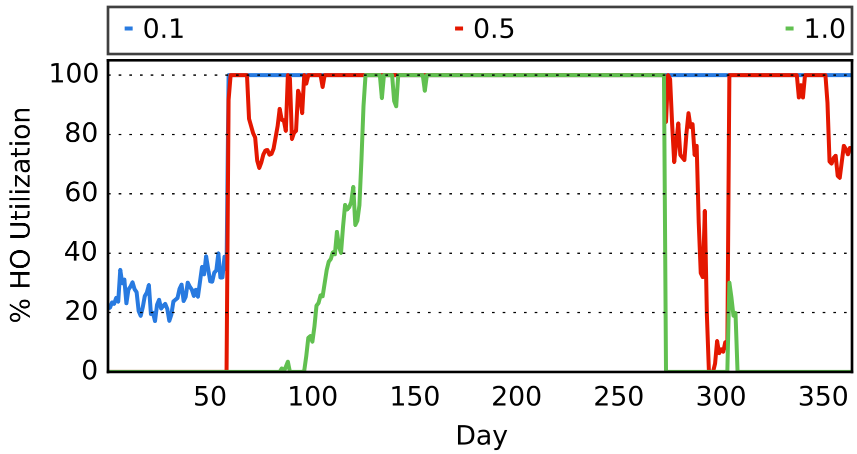

Figure 2.12: Less than 100% of heavy fuel oil is utilized on days with low energy demand. In reality, unlike this model, heavy fuel oil could be stored and used during periods of high electricity demand. The legend labels correspond to the fraction of domestic natural gas available for power generation and desalination.

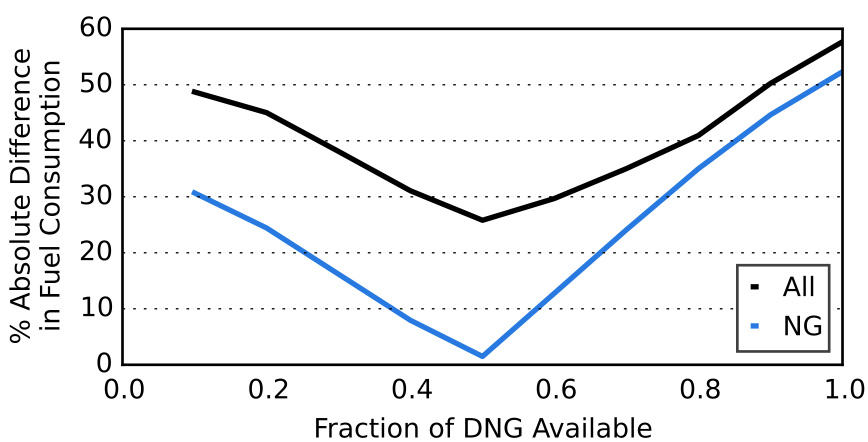

Figure 2.13: The absolute difference between the model and historical data for consumption of all fuels and for consumption of natural gas specifically is minimized when half of the domestically produced natural gas is made available for power generation and desalination.

2.4 Optimizing Fuel Allocation between Power and Desalination Plants in Kuwait

The total fuel consumed by each facility, i.e., all of the power and desalination plants at a specific location, is shown in Figure 2.14. The total energy value of the fuel consumption calculated by the model is approximately 7% less than the historical data. This difference could be the result of flaws in the model, e.g., inaccurate estimates for fuel efficiency of the power and desalination plants or lack of transmission constraints. This distinction could also be an indication that the model produces a more efficient fuel allocation scheme than the historical data, and so less fuel is needed to meet electricity and water demand. Figure 2.14 shows that less fuel is consumed at the Sabiya and Az-Zour facilities in the model output, but more fuel is consumed at the Doha facilities. The total fuel consumption at Shuaiba is very similar between the model and the historical data.

The fuel allocation can be analyzed in more detail by considering all of the different steam turbine and combined cycle power plants, as shown in Figure 2.15. Note that the open cycle gas turbines and the thermal distillation units at Shuwaikh account for less than 1% of total fuel consumption, and natural gas accounts for more than 99% of all of the fuel consumed by those plants. The most noteworthy differences between the model output and the historical data are the decrease in fuel consumption by the Doha East steam turbines and the Sabiya CCGT plant and the increase in fuel consumption by the Doha West steam turbines. The disparity with the Doha plants is

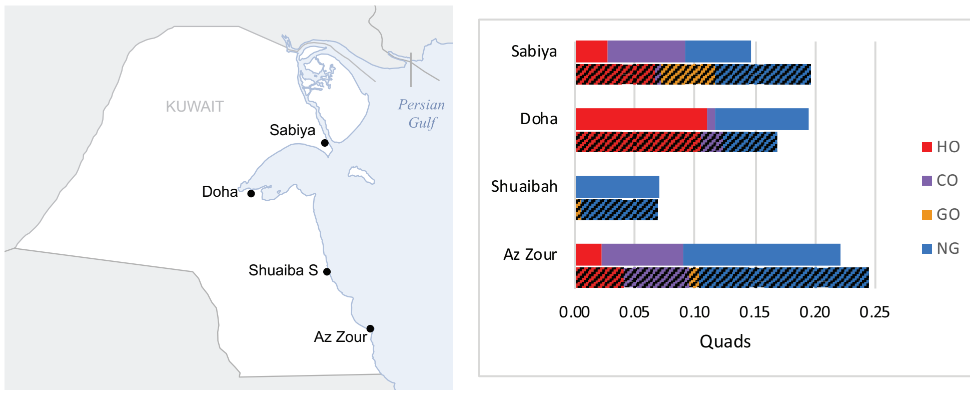

Figure 2.14: The solid bars correspond to the model output, and the hashed bars correspond to the historical data for each power generation and desalination facility. The total fuel energy consumption output by the model is approximately 7% less than the historical data.

likely based on the regression constants relating fuel consumption and power generation. Out of all of the cogeneration plants in the model, the Doha East steam turbines have the highest energy intensity for power generation, and the Doha West steam turbines have the lowest energy intensity for power generation. The reason for the significant decrease in fuel consumption by the Sabiya CCGT plant is unclear and requires further investigation.

The differences between the model output and the historical data for fuel consumption are based on differences in electricity generated and the volume of water desalinated by the plants in the model. Figures 2.16 and 2.17 show the differences between plant power generation and desalination as output by the model compared to historical data. For most of the cogeneration plants, i.e., the plants included in both Figures 2.16 and 2.17, changes in fuel consumption correspond to changes in both power generation and desalina-

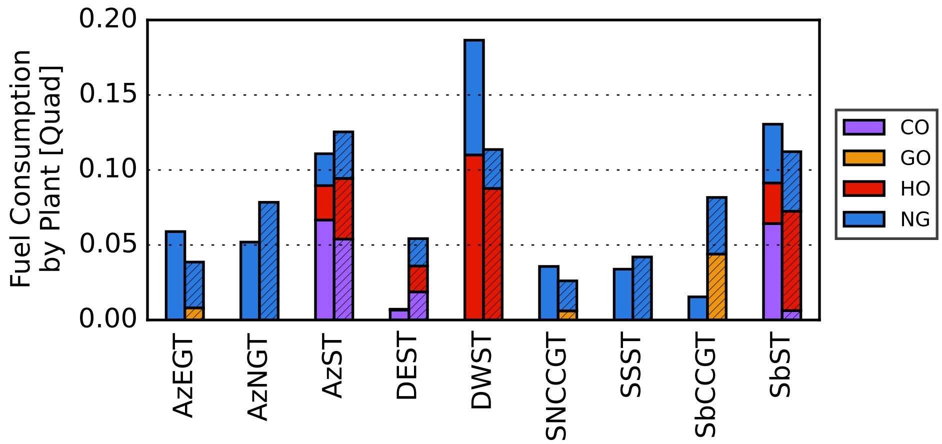

Figure 2.15: The solid bars correspond to the model output, and the right bars correspond to the historical data. The biggest disparities between the model and the historical data are with the Doha steam turbines and the CCGT plant at Sabiya.

tion volume. The steam turbines at Az-Zour, however, have decreased fuel consumption and desalination volume, but a slight increase in electricity generation. Similarly, the steam turbines at Shuaiba South have a slight decrease in fuel consumption, a significant decrease in electricity generation, and a significant increase in desalination volume. The difference in fuel consumption by the steam turbines at Doha West appears to be based mostly on increased electricity generation as well as a slight increase in desalination volume.

Figure 2.17 also includes the difference in desalination volume for the RO plants in the model compared to the historical data. Both RO plants desalinate more water in the model than in the historical data. The differences in desalination volume by facility might change if a location-specific water de-

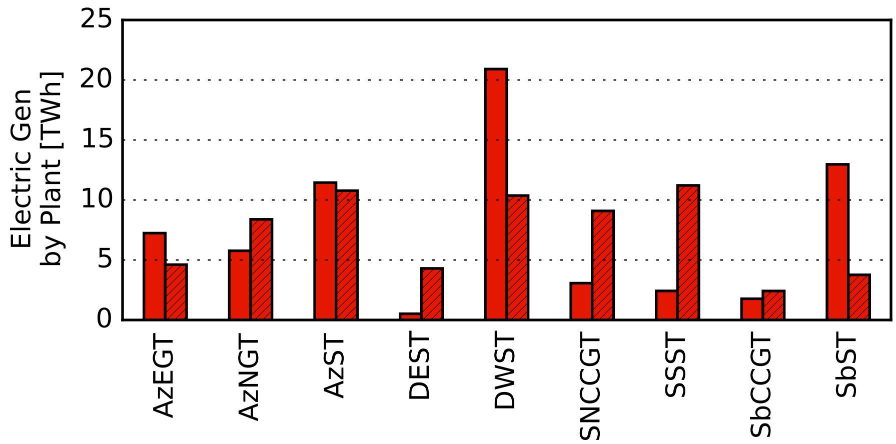

Figure 2.16: The differences in fuel consumption between the model and the historical data are partly based on the differences in plant electricity generation. The solid bars correspond to the model output, and the hatched bars correspond to the historical data.

mand constraint were included. Such a constraint would require more information about water transportation infrastructure and location-specific demand profiles for different parts of Kuwait.

A few general recommendations can be drawn from these fuel allocation results. In strict cost terms, gas oil should be used sparingly for power generation and desalination. The Doha East cogeneration plant should be used sparingly for either power generation or desalination. The RO plants should be utilized closer to full capacity and offset desalination from older, less efficient cogeneration plants.

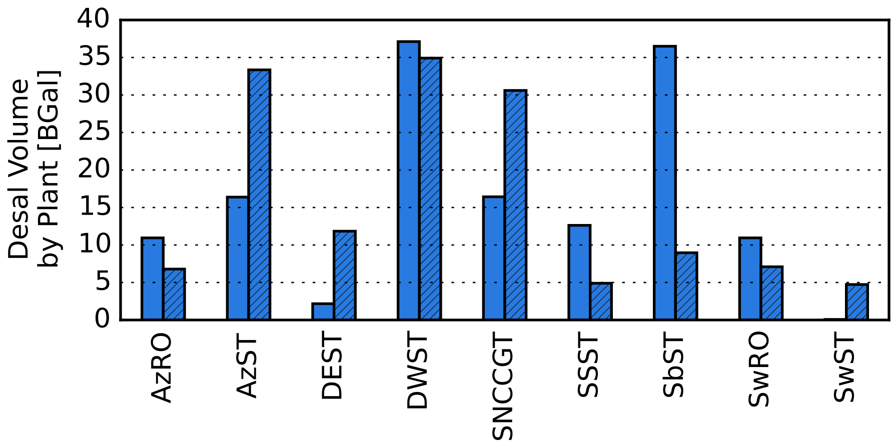

Figure 2.17: The differences in fuel consumption between the model and the historical data is partly based on the differences in plant desalination volume. The solid bars correspond to the model output, and the hatched bars correspond to the historical data.

2.4.1 Doha Case Study

The inputs to the model were modified such that the power and desalination plants at Doha could only consume natural gas. The purpose of this modification was to limit SO_2 and NO_x emissions at Doha. Figure 2.18 shows how the total fuel consumption varied by location in the case study compared to the original model. Comparing the output of the modified model to the original model, the total consumption of crude oil decreases by 42%, and the total consumption of natural gas increases by 17%. The total consumption of heavy fuel oil remains the same, but more heavy fuel oil is consumed at Sabiya and Az Zour instead of Doha.

Figure 2.19 compares the fuel consumption at each power and desalina-

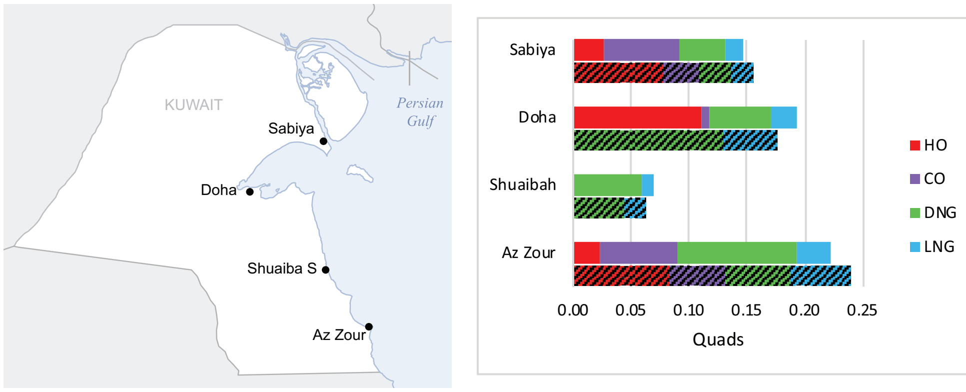

Figure 2.18: The solid bars correspond to the model output, and the hashed bars correspond to the case study. Total crude oil consumption decreases by 42%, and total natural gas consumption increases by 17% in the case study compared to the original model.

tion plant in the original model and in the Doha Case Study. Fuel consumption at Doha East decreases to nearly zero, and fuel consumption at Doha West decreases slightly, with domestic and liquified natural gas replacing heavy fuel oil. Except for the steam turbines at Shuiaiba South, which cannot burn heavy fuel oil, fuel consumption at the other steam turbines increases in the case study relative to the original model. An explanation for this change is that because the Doha plants cannot burn heavy fuel oil, more of it is available for the other steam turbines. Similarly, overall fuel consumption from gas turbine power plants decreases, particularly for the emergency gas turbines at Az Zour. An explanation for this change is that Doha West consumes more natural gas, leaving less natural gas available for the gas turbine power plants.

The change in fuel consumption corresponds to a changes in electricity generation and desalination volume at the different power plants as shown in

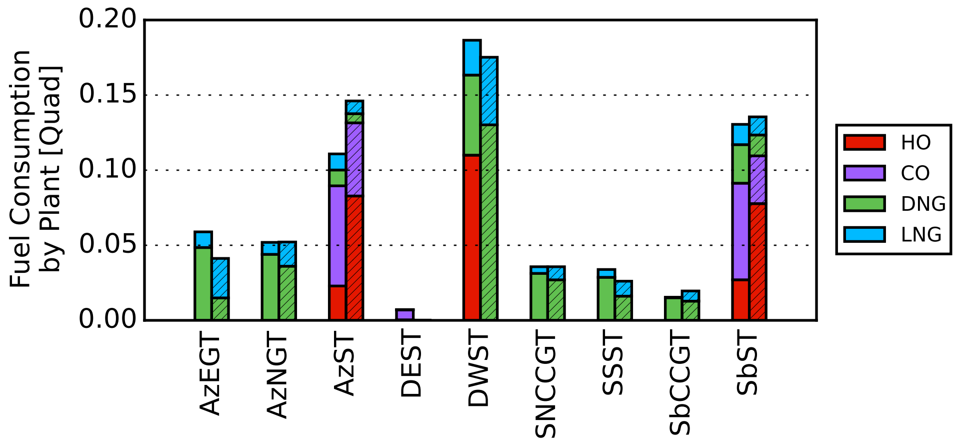

Figure 2.19: Overall, the steam turbine plants consume more fuel and the gas turbine plants consume less fuel when the Doha plants can only consume natural gas. The solid bars correspond to the original model output, and the hatched bars correspond to the case study in which the Doha power plants were only allowed to burn natural gas.

Figures 2.20 and 2.21. One noteworthy change is that while the Doha West steam turbines generate almost as much electricity in the case study as in the original model, they distill significantly less water. The operation of the RO plants is equal for the original model and the case study.

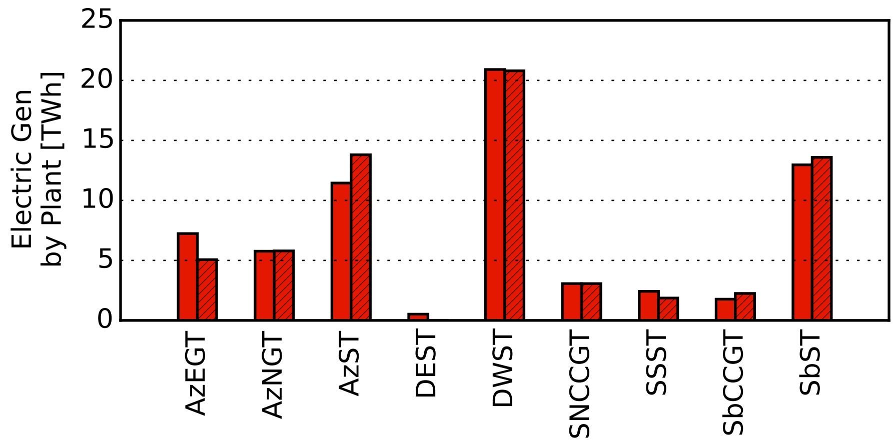

Figure 2.20: The changes in electricity generation at the different plants correspond to changes in fuel consumption. The solid bars correspond to the original model output, and the hatched bars correspond to the case study in which the Doha power plants were only allowed to burn natural gas.

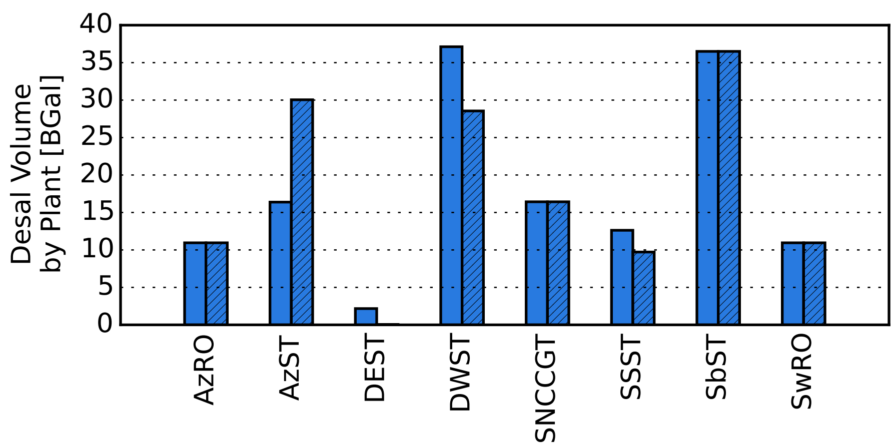

Figure 2.21: The changes in desalination volume at the different plants correspond to changes in fuel consumption. The solid bars correspond to the original model output, and the hatched bars correspond to the case study in which the Doha power plants were only allowed to burn natural gas.

The intended effect of restricting the Doha plants to consuming only natural gas in the model is to mitigate SO_2 pollution at Doha. Figure 2.22 shows that this strategy effectively eliminates SO_2 emissions at Doha. Side-benefits of this strategy include reducing CO_2 and NO_x emissions by 21% and 32%, respectively.

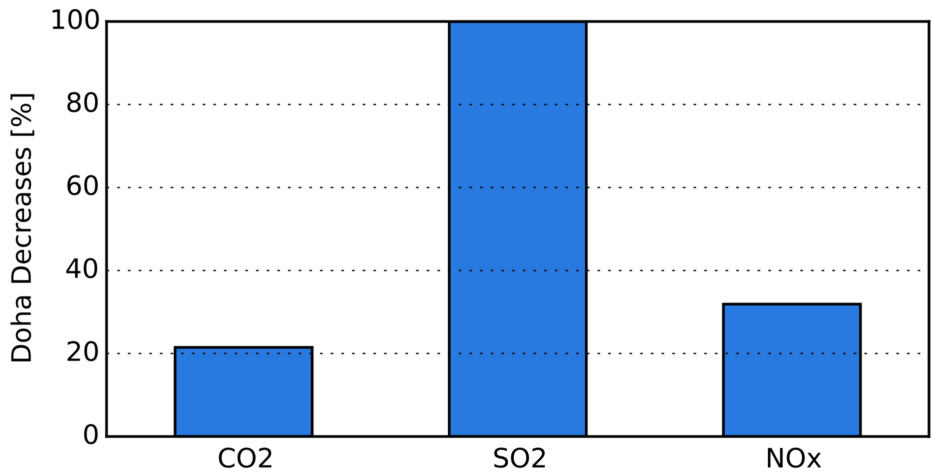

Figure 2.22: Restricting the Doha plants to burning only natural gas effectively eliminates SO_2 emissions at Doha while also reducing CO_2 and NO_x emissions by 21% and 32%, respectively.

The change in fuel consumption also results in system-wide reductions in emissions, as shown in Figure 2.23. System-wide emissions of CO_2, SO_2, and NO_x decrease by approximately 3%, 15%, and 5%, respectively. The cost of these emissions reductions an increase in fuel and O&M costs of approximately 1.3%.

Based on the results of this case study, restricting the consumption of fuels other than natural gas at the Doha power plants would have significant

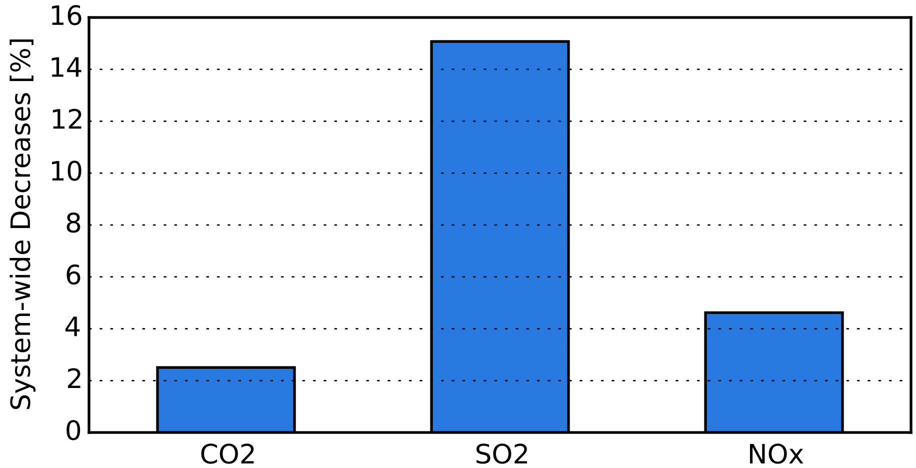

Figure 2.23: Restricting the Doha plants to burning only natural gas reduces system-wide emissions CO_2, SO_2 , and NO_x by approximately 3%, 15%, and 5%, respectively.

emission reductions at Doha and noteworthy emissions reductions system wide. The cost of these reductions would be a modest increase in fuel and O&M cost as the result of shifting generation and desalination to other plants. Because more natural gas is consumed at Doha West, less is leftover for combined cycle natural gas plants that can't burn heavy fuel oil or crude oil. As a result, the output of less efficient steam turbine power plants increases in the case study, and the output of combined cycle plants decreases in the case study.

2.5 Impact of New PV and RO Systems in Kuwait

2.5.1 Impact of Solar PV on Dispatch of Thermal Power and Desalination Plants

The hourly solar generation summed over the whole year for a given capacity of solar PV without any new RO plants is shown in Figure 2.24. This graph shows that up to 4 GW of solar PV, solar generation increases linearly with capacity. Beyond 4 GW, curtailment increases significantly, reaching approximately 29% with 16 GW of solar PV.

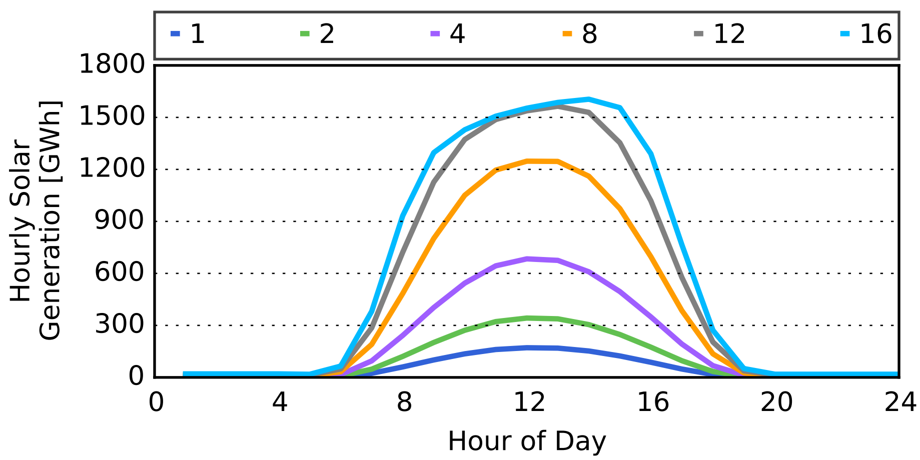

Figure 2.24: Generation from solar increases linearly with capacity up to 4 GW, beyond which curtailment increases to approximately 29%. The legend values correspond to GWs of solar PV.

The increase in hourly solar generation as a function of solar PV capacity roughly corresponds to the decrease in hourly generation from cogeneration plants as shown in Figure 2.25. This figure also illustrates the "duck curve" of reduced electricity output by cogeneration plants followed by steep ramp rates in the late afternoon. The total decrease in electricity generated by cogeneration plants is almost 22% with 16 GW of solar PV. The change in the generation profile from 12–16 GW, shown in Figure 2.25, indicates a lower bound on cogeneration electricity output. A plausible explanation for this floor is that if any more of the cogeneration steam turbines were to shut down, there would not be adequate distillation capacity online to meet demand for water. Figure 2.26 shows the average number of hours each cogeneration unit was turned on for the whole year. This figure indicates that cogeneration plants have to operate a minimum of around 5800 hours to satisfy demand constraints for desalinated water without any additional desalination capacity.

It is harder to draw general conclusions about the impact of solar PV on cogeneration desalination output. Up to 4 GW of solar PV, the hourly desalination from the cogeneration plants flattens out. Beyond 4 GW of solar, the hourly desalination profile of the cogeneration plants becomes more variable. Compared to the output of the model without any solar PV, the hourly desalination output of the cogeneration plants with 8 GW or more of solar PV on the grid decreases from the morning through the afternoon, likely the result of some cogeneration plants going completely off line.

The hourly generation profile of the power-only plants shown in Figure 2.27 explains the rest of the difference in total generation from the solar PV and cogeneration power plants. The generation profile of the power-only plants illustrates the higher flexibility of gas turbine power plants. Rather than flat or gradual changes in hourly output, the generation profile of the power-only

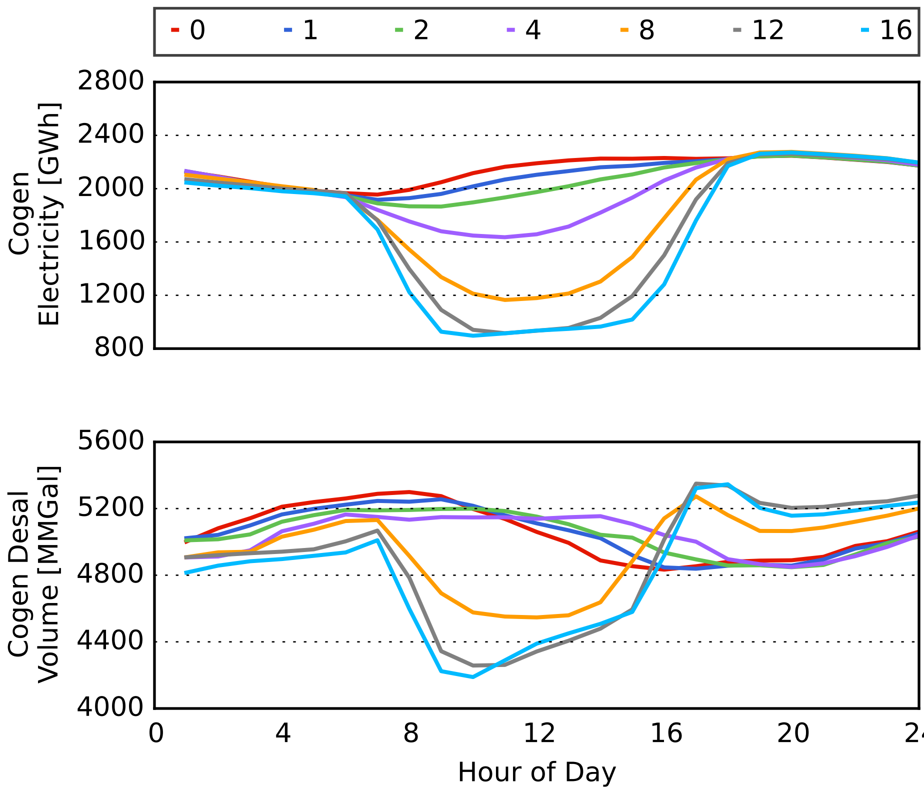

Figure 2.25: The increase in hourly solar generation as a function of solar PV capacity roughly corresponds to the decrease in hourly generation from cogeneration plants. The legend values correspond to GWs of solar PV.

plants is characterized by acute changes in hourly output, especially when there is 8 GW or more of solar PV on the grid. The decrease in total generation from power-only plants with 16 GW is just over 28%. An explanation for why the decrease in generation from power-only plants is higher than for the cogeneration plants is that the power-only plants do not need to stay online to distill water.

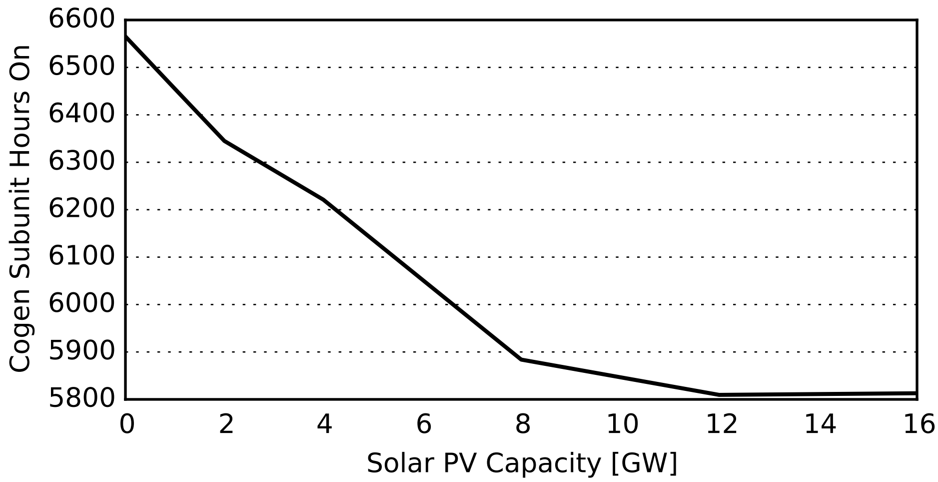

Figure 2.26: Cogeneration subunits are not turned on as often as solar PV capacity increases. This curve suggests that cogeneration plants must be turned on a minimum of approximately 5800 hours a year to meet demand for desalinated water without additional desalination capacity.

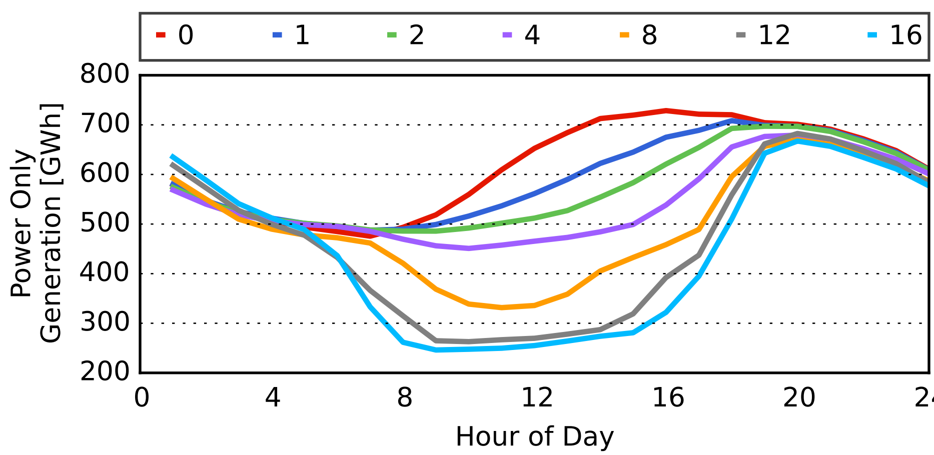

Figure 2.27: As solar PV capacity increases, the total decrease in output for power-only plants is greater than for cogeneration plants because power-only plants don't need to stay online to distill water. The legend values correspond to GWs of solar PV.

2.5.2 Synergistic Benefits of Solar PV and RO

Adding new RO capacity in Kuwait on its own would reduce the cost and emissions associated with power generation and desalination in Kuwait. This section describes how adding both new RO capacity and solar PV magnifies these benefits. The primary effect of new RO capacity is to reduce the demand for distillation from cogeneration plants as shown in Figure 2.28. With less demand for cogeneration plants to distill water, the cogeneration plants can be shut off more often, reducing the total electricity generation from cogeneration plants as shown in Figure 2.29.

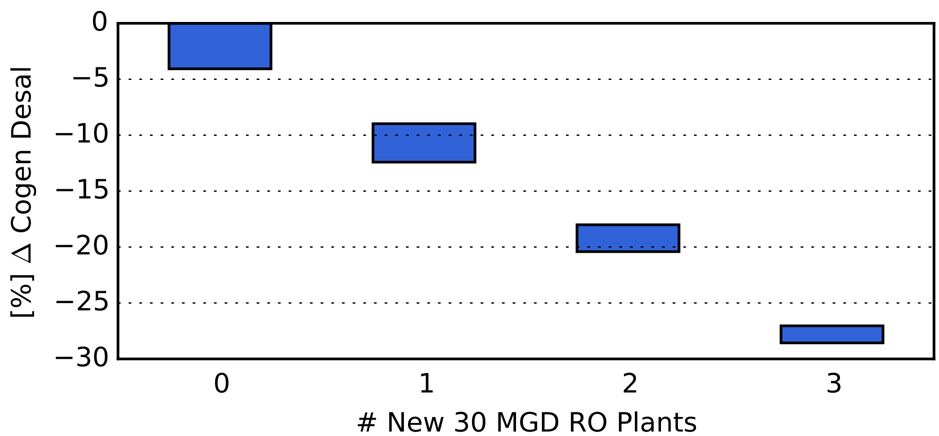

Figure 2.28: Desalination volume from cogeneration plants decreases as new RO capacity increases.

The decrease in electricity generation from cogeneration plants is made up for by increased utilization of solar PV and power-only thermal plants. Figure 2.30 shows that solar curtailment with 16 GW of solar PV decreases from almost 29% to just over 26% with three new 30 MGD RO plants. Less

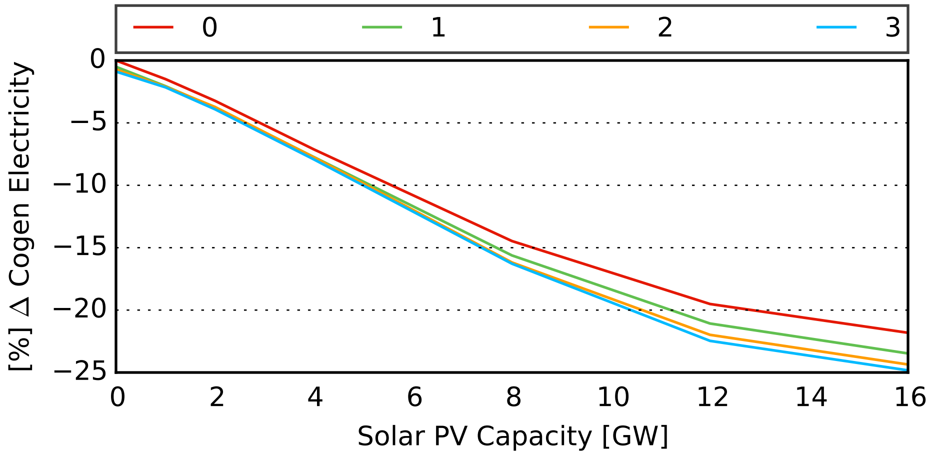

Figure 2.29: Cogeneration electricity output decreases as solar PV and new RO capacity increases. The legend values correspond to the number of new 30 MGD RO plants.

solar curtailment means that less electricity needs to be generated by thermal power plants to meet the same net demand for electricity and desalinated water. Similarly, Figure 2.31 shows that the decrease in power-only electricity generation is less significant with new RO capacity. The decrease in power-only output with 16 GW of solar is just over 21% with three new 30 MGD RO plants. The benefit of generating more electricity from the power-only plants, especially the more recent combined cycle power plants, is that they tend to be more efficient than the steam turbine power plants.

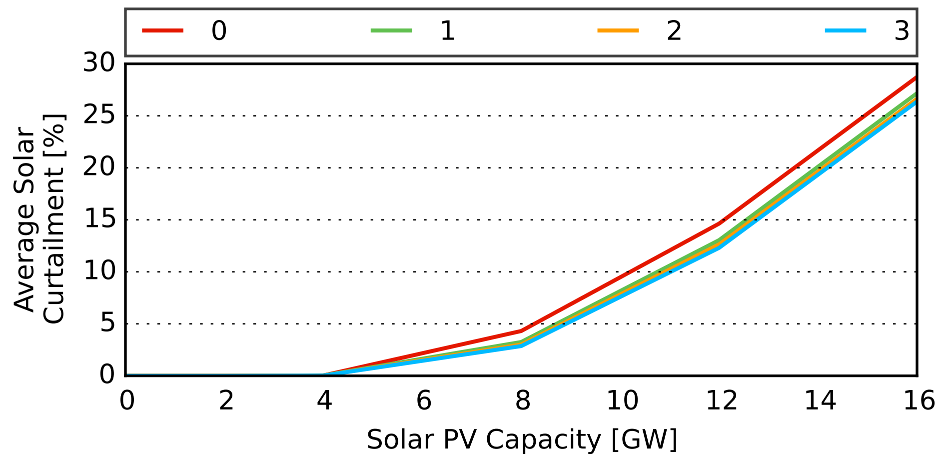

Figure 2.30: Solar curtailment decreases with each new 30 MGD RO plant. The legend values correspond to GWs of solar PV.

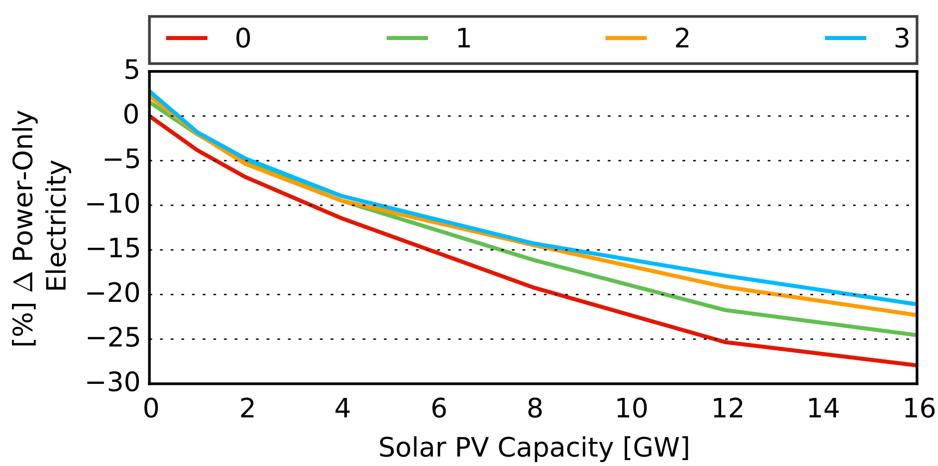

Figure 2.31: Solar PV reduces electricity generation from power-only generators, but that reduction decreases as new RO capacity increases. The legend values correspond to the number of new 30 MGD RO plants.

The effect of reduced reliance on cogeneration plants for electricity and desalination in favor of solar, combined cycle power plants, and RO, is less overall fuel consumption. Figure 2.32 shows the range of fuel reduction achievable with new PV and RO capacity. The biggest decrease in fuel consumption is from crude oil, followed by liquified natural gas and heavy fuel oil.

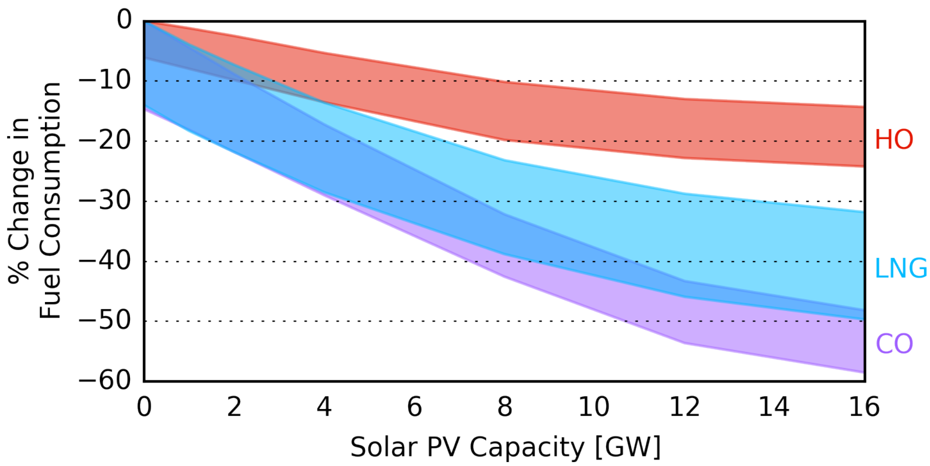

Figure 2.32: Increasing the capacity of solar PV and new RO decreases the consumption of fossil fuels for power generation and desalination in Kuwait.

Reducing consumption of fossil fuels reduces the operating cost of power generation and desalination. However, the total savings depend on the annual financing cost associated with solar PV and RO. Figure 2.33 shows the change in total system cost with solar PV and new RO. The maximum cost savings are associated with 8 GW of PV. The reason savings decrease is because the capital cost for additional units of PV increases linearly, but the increased curtailment beyond this point means that each new unit of solar PV offsets less fossil fuel consumption. Figure 2.33 indicates that each new RO plant results in an additional 3% of cost savings. These results suggest that savings could be even higher with more than three new RO plants.

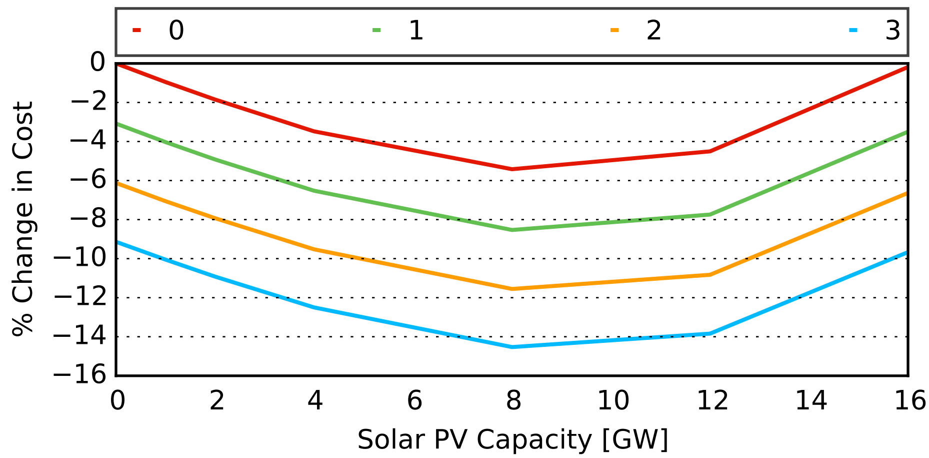

Figure 2.33: Accounting for capital cost, up to 8 GW of solar PV reduces the overall cost of power generation and desalination. Each new 30 MGD RO plant reduces cost an additional 3%.

Reducing the consumption of fossil fuels also has the effect of reducing emissions associated with power generation and desalination. Figure 2.34 shows the reduction in emissions of CO_2, SO_2, and NO_x achieved as the result of reduced fossil fuel consumption.

These results indicate that building out significant capacity of solar PV and new RO in Kuwait would reduce both cost and emissions. Reverse osmosis is less energy intensive than thermal distillation, and building new RO capacity has the effect of reducing reliance on cogeneration plants to distill water. As a result, the output of cogeneration plants can be decreased in favor of more efficient combined cycle power plants or solar PV.

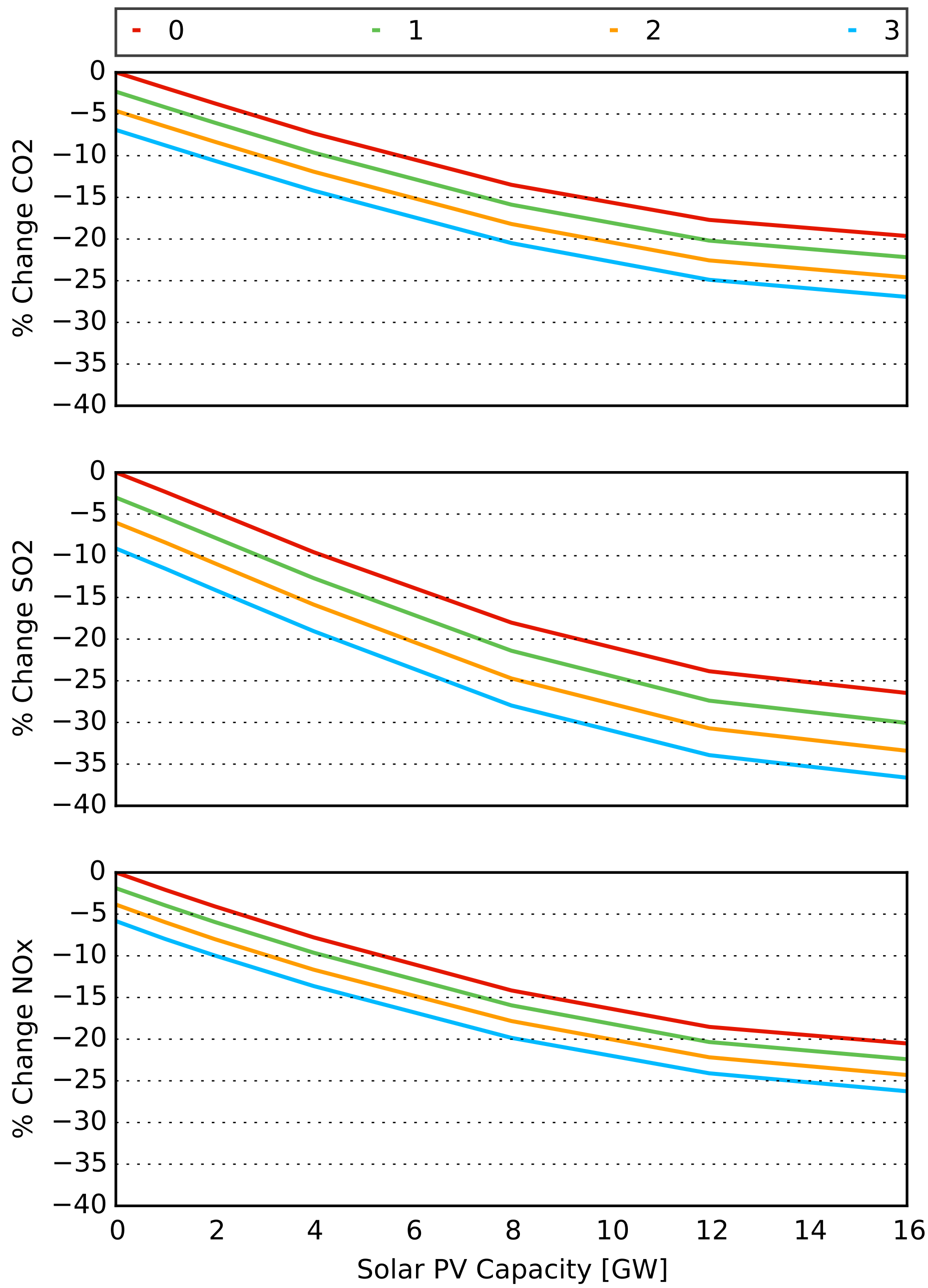

Figure 2.34: Reduced fossil fuel consumption reduces emissions of CO_2, SO_2, and NO_x.

2.6 Impact of CO_2 Taxes in Kuwait

The most significant effect of implementing a tax on CO_2 emissions in Kuwait is a shift in fuel consumption away from crude oil in favor of LNG, as shown in Figure 2.35. This effect is insignificant when the tax on CO_2 is 40 USD/ton or less. With a CO_2 tax of 100 USD/ton, crude oil consumption decreases by 79.3%, and LNG consumption increases by 144%. Figure 2.35 also shows that a CO_2 tax has virtually no effect on the consumption of heavy fuel oil. It is conceivable that if the CO_2 tax were high enough to eliminate crude oil consumption completely, heavy fuel oil would then be the "marginal fuel," meaning the consumption of heavy fuel oil would decrease with any additional increase on the CO_2 tax. However, the extent to which crude oil or heavy fuel oil can be replaced with LNG is limited by LNG import capacity.

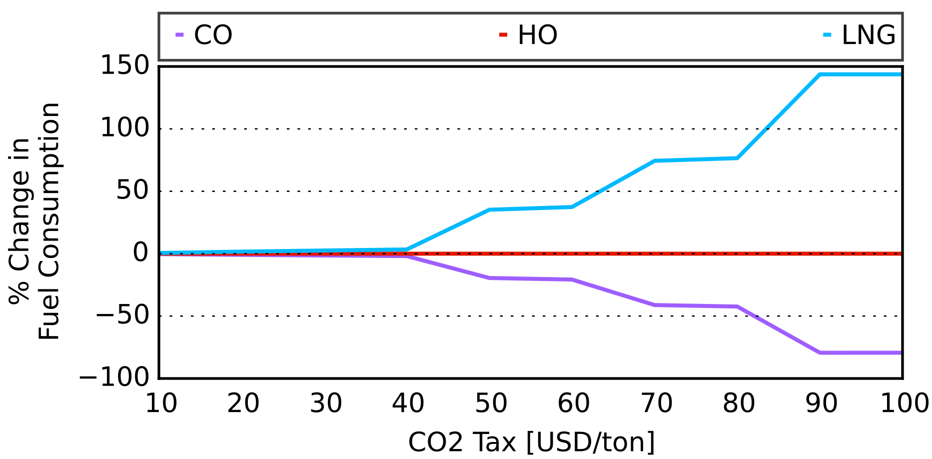

Figure 2.35: The main effect of a CO_2 tax in Kuwait is to shift consumption away from crude oil in favor of LNG.

A CO_2 tax also shifts generation in favor of the more efficient power-only plants and away from cogeneration plants as shown in Figure 2.36. With a CO_2 tax of 100 USD/ton, generation from cogeneration plants decreases by 1.4%, and generation from power-only plants increases by 4.5%.

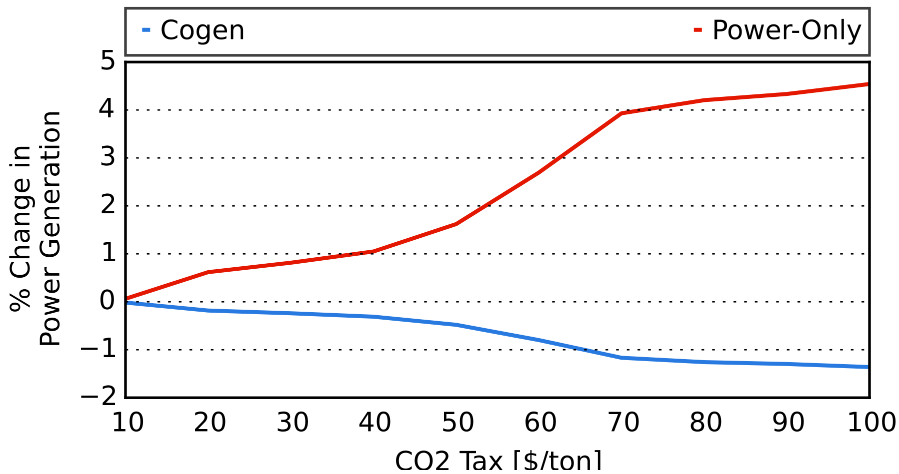

Figure 2.36: A CO2 tax tends to shift generation in favor of the more efficient power-only plants and away from cogeneration plants.

The shift in fuel consumption and in generation results in a modest increase in fuel and O&M costs system-wide, as shown in Figure 2.37. With a CO_2 tax of 100 USD/ton, fuel and O&M costs increase by 2%. A CO_2 tax above 40 USD/ton has the effect of reducing emissions of CO_2, SO_2, and NO_x, as shown in Figure 2.38. The biggest impact on emissions is on SO_2, which decreases by 29% with a 100 USD/ton tax on CO_2 compared to a 5% or 6% reduction in emissions of CO_2 and NO_x, respectively.

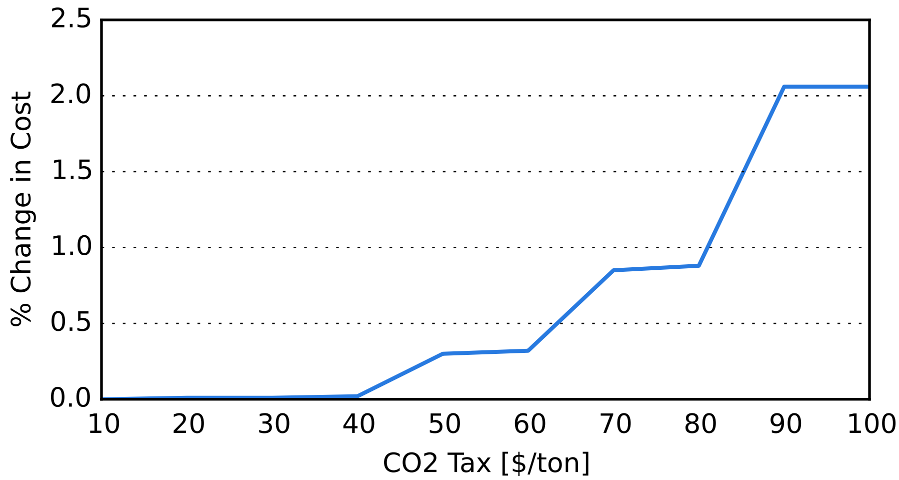

Figure 2.37: Shifting fuel consumption from crude oil to LNG and generation from cogeneration in to power-only has a modest impact on system-wide fuel and O&M costs.

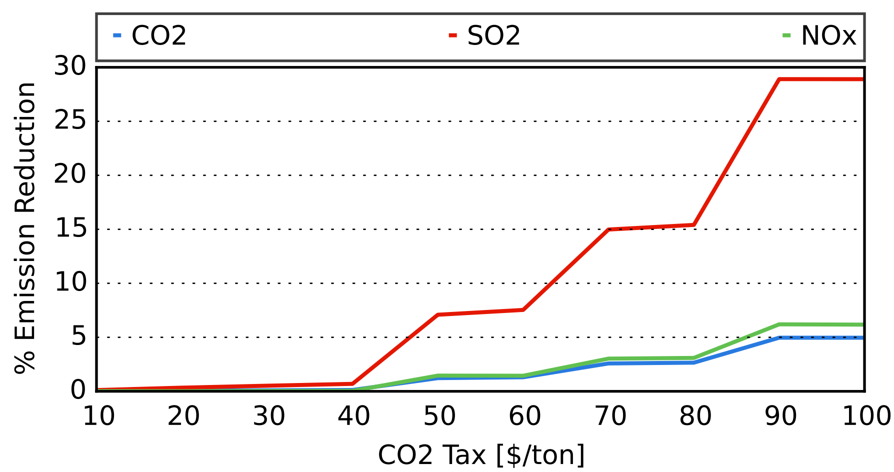

Figure 2.38: A CO2 tax above 40 USD/ton has the effect of reducing emissions of CO_2, SO_2, and NO_x.

2.7 Conclusions

2.7.1 Summary

This chapter starts with an overview of the history and present status of oil production, desalination, and power generation in Kuwait. The purpose of this overview is to provide context for Kuwait's interest in finding strategies to reduce the cost and environmental impact of their power generation and desalination systems. That overview is followed by a review of the academic literature regarding modeling techniques for simulating systems with characteristics similar to the power and desalination systems in Kuwait.

The background section is followed by a mathematical description of a unit-commitment model used to simulate Kuwait's power generation and desalination systems. This model is unique in that it optimizes fuel allocation among Kuwait's power and desalination plants and simultaneously optimizes the dispatch schedule for power and desalination plants in Kuwait so as to minimize total system cost. The description of the model also includes an overview of the data sources and assumptions used as inputs for the model. The model description is followed by an overview of the model "calibration." In lieu of more detailed information about the availability of different fuels used by power and desalination plants in Kuwait in Kuwait, the inputs to the model were tuned so that the model approximated the historical operation of Kuwait's power generation and desalination systems.

The description of the model is followed by three analyses of Kuwait's power and desalination systems with the objective of identifying strategies for

Kuwait to manage the economic and environmental impact of the energy consumption associated with these systems. The first of these analyses compares the allocation of fuel among power and desalination plants in Kuwait as output by the model to the historical data. This analysis indicates that gas oil and the Doha East cogeneration plant should be used sparingly for either power generation or desalination. This analysis also indicates the RO plants should be operated closer to full capacity to offset desalination demand from older, less efficient cogeneration plants.

This analysis is followed by a case study in which the model is modified so that the Doha power and desalination plants can only consume natural gas to mitigate local SO_2 emissions. This case study indicates that restricting the Doha facilities to consuming only natural gas would result in significant local emissions reductions at Doha as well as noteworthy emissions reductions system-wide. Such a strategy would almost totally eliminate SO_2 emissions from the Doha facilities while also reducing system-wide emissions of SO_2 by approximately 15%. Another impact of restricting fuel consumption at Doha is that the system-wide output of steam turbine power plants increases while the output of gas turbine power plants decreases. The explanation for this change is that because the Doha plants cannot consume heavy fuel oil, more of it is left over for the other steam turbine power plants. Similarly, because the Doha West cogeneration plant consumes more natural gas, less natural gas is available for the gas turbine power plants. These changes in power plant output and fuel consumption result in a 1.3% increase in fuel and O&M costs.

The second analysis estimates the economic and environmental impact of building solar PV and new RO capacity in Kuwait. This analysis indicates that adding up to 8 GW solar PV to Kuwait's power grid can reduce fossil fuel consumption, leading to cost savings and emissions reductions. However, beyond 8 GW of solar PV, the fuel savings are not sufficient to account for the additional capital cost because solar curtailment starts to increase significantly and is as high as 29% annually with 16 GW of solar. The main reason for solar curtailment is that the cogeneration plants have to run a total of approximately 5800 hours per year on average to meet demand for desalinated water.

Building new RO capacity in addition to solar PV has numerous benefits. The direct effect of building new RO capacity is to reduce the energy intensity of desalination, because RO is less energy intensive than thermal distillation. By reducing demand for cogeneration plants to produce desalinated water, the cogeneration plants can be shut off more often in favor of more efficient combined cycle power plants and solar PV. Thus, new RO reduces the energy intensity and fuel consumption associated with both desalination and power generation systems in Kuwait. Each new 30 MGD RO plant results in approximately 3% reduction in system fuel and O&M costs and decreased emissions of CO_2, SO_2, and NO_x.

The third analysis in this chapter estimates the impact of a CO_2 tax ranging from 10–100 USD/ton on Kuwait's power generation and desalination systems. This analysis indicates that a CO_2 tax of more than 40 USD/ton has the effect of reducing crude oil consumption in favor of LNG. A 100 USD/ton

CO_2 tax leads to a 79% decrease in crude oil consumption and a 144% increase in LNG consumption. This shift in fuel consumption results in decreased emissions from CO_2, SO_2, and NO_x. A CO_2 tax also has an impact on the dispatch of power plants in Kuwait. With a 100 USD/ton CO_2 tax, generation from cogeneration plants decreases by 1.4%, and generation from power only plants increases by 4.5%. The shift in fuel consumption and power plant dispatch results in a modest increase in fuel and O&M cost.

2.7.2 Future Work

This analysis used a unit-commitment model to simulate the operation of power and desalination plants in Kuwait and to investigate strategies for reducing the cost and emissions associated with these facilities. Several changes could improve the validity of this model. For example, this model used a multi-linear regression with gross power output and desalination volume as the independent variables to estimate the hourly fuel consumption for each power and desalination plant. Such a formulation does not take into account the change in plant efficiency as a function of output. In reality, power plants tend to be less efficient when running at low output [24]. A polynomial formulation of fuel consumption as a function of gross power output and desalination volume would account for this relationship, but such a formulation is more computationally expensive. Future work should consider computationally tractable formulations of the fuel consumption constraint that takes into account the variation in plant efficiency as a function of output.

Another way this model could be improved would be to include more realistic constraints for the availability of crude oil for power generation and desalination plants. This model doesn't include any limits on the consumption of crude oil, and, as a result, the solution of the model has higher crude oil consumption than the historical data. One reason why the availability of crude oil might be limited is that some percentage of crude oil production is guaranteed to foreign buyers through export contracts. Including such a constraint would require more detailed information about export contracts.

Another way this model could be improved would be to incorporate a scheme for liquid fuel storage. This model defines a daily availability of fuel oil based on historical fuel oil consumption. A shortcoming of this formulation is that unused fuel is lost and unavailable for future consumption. Instead, this fuel could be be purchased and stored. A simple way to incorporate fuel storage would be to roll over unused fuel into the availability of fuel for the next day. A more realistic implementation would allow for fuel to be purchased in advance in anticipation of future high fuel prices or electricity demand. Such an implementation would require a degree of foresight not currently included in the model.

The inputs to this model are based on data from 2014. Since this model was initially put together, more recent data has become available. Among the changes are decreased fuel prices and new generating capacity. The price of LNG in particular has changed significantly, to the point that it is may be cheaper than any of the alternatives except domestic natural gas. This model could be improved by updating the inputs to reflect the most recent data.

The minimum power output constraint in this model is set to 40% of rated capacity for each power plant subunit. Depending on how each cogeneration plant is designed, it is conceivable that the minimum output for each steam turbine could be even lower. Future work should incorporate more detail of how the cogeneration plants in Kuwait are designed so that the minimum power output can be more realistically defined.

The unit-commitment model used in this analysis does not include any constraints on transmission for either electricity or for natural gas. Such constraints could alter the output of the model to be closer historical operation of power and desalination plants in Kuwait. Including such constraints would require much more information about transmission capacity in Kuwait.

Unit-commitment models are useful for realistically simulating power systems on time-scales of minutes to hours. However, investigating new capacity additions requires re-running the model for every permutation of capacity additions. Another strategy for predicting the most optimal capacity additions would be to use a capacity expansion model. Such a model would use estimates for future electricity and water demand as inputs and would have investments in new capacity as a decision variable. A capacity expansion model would be useful for estimating which capacity investments would be most cost effective given different assumptions on demand growth or policy changes such as emissions taxes.

This research considered the impact of building solar PV and new RO capacity in Kuwait. Another avenue for research would be to consider the cost-effectiveness of retrofitting Kuwait's existing infrastructure. For example, steam turbine cogeneration plants could be retrofitted into combined cycle power plants. Combined cycle power plants are more efficient, but they can only burn natural gas or gas oil, which may result in increased fuel costs. Another retrofitting concept would be to investigate whether electricity generated by solar PV that would otherwise be curtailed could be used to preheat seawater to reduce the energy intensity of distillation. Such a scheme could reduce the fuel consumption associated with desalination and allow more solar PV to be cost-effectively integrated into Kuwait's power grid.

Chapter 3

Systems-Level Thermodynamic and Economic Analysis of a Seawater Reverse Osmosis Desalination Plant Integrated with a Combined Cycle Power Plant

3.1 Background

This study includes thermodynamic and economic analyses of a seawater reverse osmosis (RO) desalination plant integrated with a small-scale combined cycle natural gas turbine power plant (CCGT). Approximately 27% of the global population lives within 100 km of the coast and less than 100 m above sea level, making seawater desalination a viable alternative to conventional freshwater sources for much of the population [47]. At the same time, demand for water and electricity is increasing, and an integrated power generation and desalination facility can help address both needs simultaneously [6,48]. There are several motivations for integrating a desalination plant with a power plant. Depending on the specific arrangement of the desalination and power plants, an integrated facility might benefit from a variety of different features including shared site permits and intake infrastructure and greater utilization of waste energy streams, which can reduce the cost and environmental impact of having two separate facilities. Desalination is more energy intensive and has a greater "carbon footprint" than conventional water treatment, but an RO plant integrated with a CCGT plant can be less carbon intensive than an RO plant that uses electricity from a grid that is reliant on generation from coal or oil-fired power plants [9, 10]. Additionally, the facility's operation and participation in both electricity and water markets can be optimized to maximize profitability while meeting demand for electricity and water.

There are numerous desalination plants worldwide that are integrated or colocated with power plants. For example, the Tuaspring Reverse Osmosis desalination plant in Singapore has a capacity of 319 thousand cubic meters per day (TCM/d) that is integrated with a 411 MW combined-cycle natural gas plant [49]. In the U.S., the Tampa Bay Seawater Desalination plant has a capacity of 95 TCM/d and shares intake infrastructure with Tampa Electric's Big Bend Power Station, a 1700 MW coal plant [14, 15]. By sharing intake infrastructure, the feedwater for the RO plant can be preheated by using it as the coolant for the condenser of the power plant, and preheating the feedwater decreases the specific energy consumption of desalination [50].

This study seeks to answer several questions about the technical and economic tradeoffs of integrating a seawater RO plant with a small-scale CCGT plant. First, the flow rate of seawater required for the cooling system of a small-scale CCGT plant is compared to the feedwater flow rate of seawater going into a seawater RO plant. If the flow rate of coolant is less than the flow rate of feedwater for the RO plant, the CCGT plant can share a seawater intake with the RO plant. Otherwise, the CCGT plant would require additional seawater intake capacity or have to use a closed-loop cooling system with a cooling tower. Regulations on intakes for power plant cooling systems such as section 316(b) of the Clean Water Act in the U.S. tend to restrict the use of open cycle cooling systems [51]. A downside of closed-loop cooling systems with a cooling tower is that they consume more water than open-loop systems [52]. Cooling towers can use saltwater instead of freshwater, but using saltwater increases the maintenance cost and decreases the performance of the cooling tower [53]. Second, this study includes an estimate of the carbon intensity of a small-scale CCGT plant compared to the average carbon intensity of electricity purchased from the Texas power grid. Even though a natural gas fueled power plant generates carbon emissions, the carbon intensity should be less than electricity purchased from a power grid that is still heavily reliant on coal burning power plants.

Lastly, an optimization analysis and levelized cost of water (LCOW) framework is used to estimate the cost of an RO plant integrated with a small-scale CCGT plant compared to a standalone RO plant. This framework takes into account the capital and operating costs associated with a seawater RO plant, the cost of powering an RO plant with electricity generated by a small-scale CCGT plant or purchasing electricity from the grid, the capital and fixed costs associated with a small-scale CCGT plant, and the revenues that can be earned by selling electricity to the grid. This type of cost analysis is called a "credit method" because the revenues that can be earned by selling electricity to the grid are credited against the costs of desalinating water [54]. This analysis considers the hourly wholesale price of electricity, and an optimization model is used to schedule the operation of an integrated CCGT-RO so as to maximize revenues from electricity sales while also achieving a prescribed capacity factor for the RO plant. This analysis differs from other cost analyses that only consider the average price at which electricity can be sold to the grid, such as the International Atomic Energy Agency's "Desalination Economic Evaluation Program" (DEEP) [55].

This study builds on the body of research on integrated power generation and desalination plants and relies on existing reports for the cost and specific energy consumption of desalination. A wide range of real-world costs and cost estimates for desalination has been reported in the literature [56–60]. The cost of desalination has tended to decrease over time, particularly with improvements to RO technology in recent decades. The cost of desalination depends on a number of factors including the type of desalination technology, the capacity and availability of the desalination plant, and the cost of energy. The cost of desalination varies based on site-specific factors such as feedwater quality and the cost of intake and outfall systems [56]. The cost of energy depends on the specific energy consumption of the desalination plant and the cost of electricity used to power the desalination plant. The specific energy consumption of a desalination plant depends on a number of factors including the type of desalination technology, the quality and temperature of feedwater, the length of intake, the recovery ratio, and the use of energy recovery devices such as pressure exchangers [8, 23, 61]. In general, the specific energy consumption of RO is lower than for thermal desalination technologies such as multiple stage flash (MSF) or multiple effect distillation (MED).

Much of the literature on integrating desalination plants with power plants focuses on fossil fuel burning cogeneration or “dual-purpose” power and desalination plants wherein low-pressure steam is removed from the power cycle and used as the heat source for a thermal desalination plant [54, 62–66]. This kind of arrangement is common in the Persian Gulf countries because of its reliability and the availability of cheap energy [60]. There are also numerous studies that consider or focus on fossil fuel power plants integrated with an RO plant [62, 63, 65–67]. These studies include in depth analysis of the thermodynamic efficiency and economics of cogeneration power and desalination plants. Some of these studies also include an optimization analysis to determine the optimal design of a cogeneration plant with constraints on water and electricity production [54,62,63]. Several of these studies use the International Atomic Energy Agency’s DEEP cost estimating tool, which can estimate the cost of desalination for different technologies based on a variety of parameters including feedwater quality, fuel cost, and power plant availability [55, 65, 67]. The DEEP cost estimating tool also estimates revenues earned from electricity sales based on an average price of electricity.

There are also many articles focused on integrating desalination plants with nuclear power plants [65, 68–72]. These studies consider the prospects for integrating desalination systems, both thermal and RO, with existing nuclear power plants as well as the potential for integrating desalination plants with next generation nuclear technologies. There are both economic and environmental motivations for these studies to focus on integrating desalination systems with nuclear power plants instead of fossil fuel burning power plants. Nuclear power plants do not emit carbon dioxide, and nuclear power plants are cheaper to operate than fossil fuel burning power plants in terms of fuel and variable operation and maintenance cost per unit of electricity generated [46]. Some of these analyses also take advantage of the DEEP cost estimating tool to estimate that the cost of desalination with nuclear power is lower than the cost of desalination with fossil fueled power plants, particularly when the cost of environmental externalities are also taken into consideration [65, 72]. However, these studies do not account for the capital cost associated with building new nuclear plants.

Much of the research on integrating desalination plants with fossil fuel and nuclear power plants focuses on large, commercial-scale power plants. The focus on commercial-scale plants can possibly be explained by the fact that many of large power plants have already been built and are operating worldwide, and so integrating desalination plants into these existing systems would not require investment in new power generation capacity. Commercial-scale power plants also tend to be more efficient than smaller power plants, resulting in lower energy costs for desalination. What these analyses fail to address, however, is whether it is cost-effective to build new power generation capacity specifically for the purpose of powering a desalination plant. A major technical difference between large and small-scale power plants is the flow rate of water needed for a once-through cooling system. While a large power plant may need a much higher flow rate of cooling water than can be processed by a desalination plant, a small-scale power plant needs a much lower flow rate of cooling water and may be able to share an intake with a desalination plant.

In addition to fossil fuel and nuclear power plants, there have also been many studies focused on integrating desalination plants with renewable sources such as wind, solar, and geothermal energy [73–77]. Like with nuclear plants, one of the motivations for integrating desalination systems with renewables is that they don't emit carbon dioxide. Another benefit of renewable energy systems is that they may be better suited than large power plants for providing energy in remote locales that aren't connected to a power grid. However, the intermittency of renewable energy sources like wind and solar results in a lower capacity factor for the RO plant, which results in a higher LCOW. For example, the capital cost for a 1000 TCM/d RO plant with a capacity factor of 50% is twice as much as a 500 TCM/d RO plant with a capacity factor of 100%, even though both plants produce the same amount of water on average.

With the exception of Gold et al., the existing literature lacks much consideration of the time-dependency of electricity demand and the price of electricity [73]. Such time-dependent factors have a significant effect on how an integrated power generation and desalination plant would optimally operate with the objective of minimizing operating costs and maximizing revenues from electricity sales. In general, an integrated power generation and desalination facility would tend to schedule the operation of the desalination plant around peak electricity demand and sell electricity to the grid instead.

While the analytical framework presented in this manuscript is generalized in nature, it is illustrated for a site in Texas for several reasons. Texas annual water demand is projected to grow by more than 17% from 2020–2070, and Texas electricity demand is projected to grow by almost 14% by as early as 2025 [78, 79]. Thus, there is a need for additional water and electric power capacity. Since 2003, the Texas Water Development Board has had a mandate to research the feasibility of investing in desalination as a means of increasing the state water supply [80].

Even though the high cost and specific energy consumption for desalination has historically made it an unattractive water supply option compared to conservation or treating water from other sources, the availability of relatively affordable natural gas and ability to participate in a competitive power market might improve the economic viability of a desalination plant integrated with a CCGT power plant in a state expecting severe water stress [78,81]. This analysis focuses on the power market managed by ERCOT, the Electric Reliability Council of Texas, which accounts for about 90% of the state's electric load [82]. ERCOT is responsible for managing the grid and settling the buying and selling of electricity on a wholesale market. Retail electric providers (REP) who purchase electricity on one of the ERCOT wholesale markets can then sell the electricity to end-users at a contracted rate.

3.2 Methods

3.2.1 Integrated CCGT-RO plant specifications

A schematic of an RO plant integrated with a CCGT plant is shown in Figure 3.1. The CCGT plants considered for this analysis are based on the Siemens Gas Turbine line – SGT 600, 700, and 800, specifically – because of the suitability of these gas turbines for combined cycle applications, the availability of performance and cost related data, and a range of sizes capable of running a large-scale seawater RO plant [83]. The maximum power output, $\dot{W}_{max}$, HHV efficiency, η_{HHV}, and overnight capital cost, OCC, of the CCGT plants were taken from the Gas Turbine World Handbook [84]. These specifications are shown in Table 3.1.

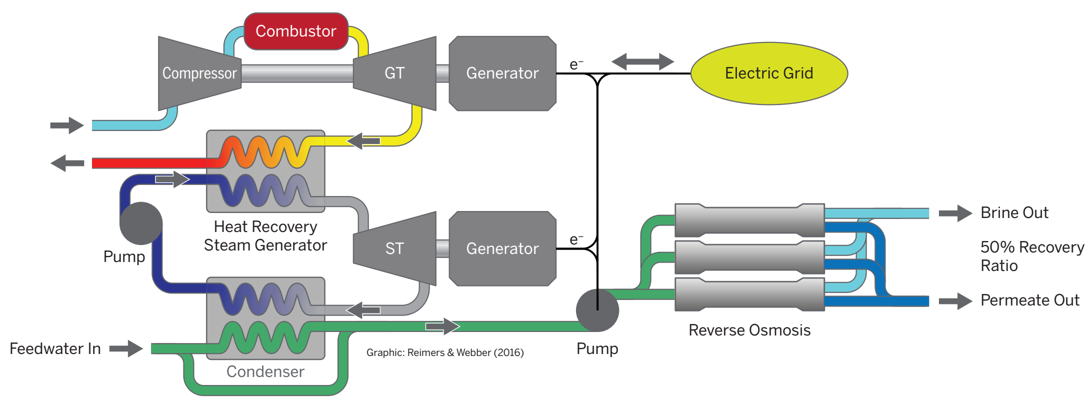

Figure 3.1: For an RO plant integrated with a CCGT plant, electricity generated on site can be used to power the RO plant or sold to the grid. (GT = gas turbine; ST = steam turbine)

The maximum power output of the CCGT was used to determine the maximum RO capacity, $\dot{V}_{RO,max}$, that could be powered by the CCGT, as shown in equation 3.1:

Table 3.1: The maximum power output, $\dot{W}_{max}$, HHV efficiency, η_{hhv}, and overnight capital cost, OCC, of the CCGT plant were taken from the Gas Turbine World Handbook. Note that HHV efficiency for the power plants are used to agree with the prices for natural gas, which are based on HHV.

SGT Model	$\dot{W}_{max}$ [MWe]	η_{hhv}	OCC [$/kW]
600	35.9	0.45	1359
700	45.2	0.47	1277
800	71.4	0.50	1091

$$\dot{V}_{RO,max} = \frac{\dot{W}_{max}}{E_{RO}} \tag{3.1}$$

where E_{RO} is the specific energy consumption of the RO plant. Note that the units for flow rates in the model are in thousand cubic meters per hour. This analysis assumes a specific energy consumption of 3.05 kWh/m^3 for both the standalone RO plant and CCGT-RO plant [23]. Note that that the specific energy consumption of the integrated CCGT-RO plant could be slightly lower because of the feedwater being preheated with waste heat from the CCGT condenser [50]. This effect is assumed to be negligible because of the significantly lower cooling water flow rates compared to the overall flow rate of feedwater for the RO plant.

This analysis assumes that the RO plant would have a recovery ratio between 40-50%, i.e., 40-50% of seawater intake is output as freshwater permeate, as indicated in Figure 3.1 [85, 86]. The recovery ratio, RR, is used to calculate the intake size needed to accommodate the maximum RO capacity as shown in equation 3.2:

$$\dot{V}_{in} = \frac{\dot{V}_{RO,max}}{RR} \tag{3.2}$$

where $\dot{V}_{in}$ is the maximum flow rate of seawater intake.

3.2.2 Coolant flow rate and carbon emissions

The coolant flow rate for the CCGT plant was estimated using a thermodynamic model built in Thermoflex, a commercial software package for modeling thermal systems [87]. Thermoflex includes numerous sample models of thermal systems, including a model of a basic CCGT plant. Thermoflex also has a gas turbine library that includes performance specifications for many of the gas turbines on the market. The basic CCGT model was modified to include the Siemens gas turbines described in Table 1 and to include an open cycle cooling system rather than a cooling tower. Site conditions based on typical weather data for the Texas Gulf Coast region were also used as inputs to the Thermoflex model. Weather inputs include ambient temperature, 21 °C, seawater temperature, 20 °C, and relative humidity, 75% [88, 89]. A detailed image and a description of the Thermoflex model is included in the Appendix. After selecting a gas turbine and setting the site conditions, the model was run to determine the flow rate of coolant into the CCGT plant. The coolant flow rate for the CCGT plant was compared to the total flow rate of seawater into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO.

The carbon intensity of the CCGT plant, CI_{CCGT}, was estimated using

EIA's reported values for the carbon intensity of natural gas, CI_{ng} , approximately 181 kg/MWh_{th} , and the efficiency of the CCGT plant as shown in equation 3.3 [90].

$$CI_{CCGT} = \frac{CI_{ng}}{\eta_{HHV}} \tag{3.3}$$

For a standalone RO plant, the carbon emission intensity of electricity purchased from ERCOT was estimated to be approximately 584 kg/MWh_e based on EIA's estimated emissions associated with power generation in the state of Texas averaged from 2011–2015 [91]. Note that marginal emissions associated with a new RO plant in Texas would depend on the dispatch of power plants to meet the RO plant load and not just the fleet average emissions for ERCOT.

3.2.3 Economic Analysis

An optimization analysis was used to determine how an integrated CCGT-RO plant would operate on an hourly basis with the objective of minimizing the net cost of desalination. The results of this optimization analysis were used to estimate the levelized cost of water (LCOW) for an integrated CCGT-RO plant compared to a standalone RO plant. Data from Global Water Intelligence's `DesalData.com` were used to estimate the operating cost of a seawater RO plant, CRO, which includes the cost of chemicals, labor, replacement parts, and membranes as shown in Table 3.2 [92].

Table 3.2: The operating costs for chemicals, labor, parts, and membranes were taken from the cost estimator on *Global Water Inteligence*'s DesalData.com, and the sum of these values is defined as C_{RO}. All values are in ¢/m^3 of permeate.

Component	Unit Cost ¢/m^3
Chemicals	7.0
Labor	6.7
Parts	3.0
Membranes	3.0
Total	**19.7**

As for the cost associated with powering an RO plant, this analysis assumes that a small-scale CCGT plant could be used to power an RO plant or sell electricity into the wholesale electricity market. Conversely, this analysis assumes that a standalone RO plant would have to purchase electricity from a retail electric provider (REP) or through a power purchase agreement with a generator. Texas-specific energy prices were used for this study, but this analysis could be repeated using any electricity price data derived from an auction-based wholesale market and associated retail rates for fuel and electricity. The cost of powering a standalone RO plant, $C_{power,sa}$ is defined by equation 3.4:

$$C_{power,sa}(t) = P_{elec,buy}(t) \times W_{RO,sa}(t) \tag{3.4}$$

where $W_{RO,sa}$ is the hourly electrical energy consumed by a standalone RO plant, and the retail price for electricity, $P_{elec,buy}$ is taken from EIA's monthly average prices for industrial customers in Texas for 2011–2015 [93]. The hourly electricity consumed by a standalone RO plant is the product of the volume of water desalinated, VRO, and the specific energy consumption of desalination as shown in equation 3.5.

$$W_{RO,sa}(t) = V_{RO}(t) \times E_{RO} \tag{3.5}$$

The cost of powering an integrated CCGT-RO, $C_{power,int}$, is defined by equation 3.6, and the revenues that can be earned from electricity sales, R_{elec}, are defined by equation 3.7:

$$C_{power,int}(t) = \left(\frac{P_{ng}(t)}{\eta_{HHV}} + V_{O\&M}\right) \times W_{gen}(t) \tag{3.6}$$

$$R_{elec}(t) = P_{elec,sell} \times W_{sell}(t) \tag{3.7}$$

where W_{gen} is the hourly electrical energy generated by the CCGT, and W_{sell} is the hourly electrical energy sold to the grid. The retail price for natural gas, Png, is taken from EIA's monthly average prices for industrial customers in Texas, and the wholesale electricity prices, $P_{elec,sell}$, are based on ERCOT's day-ahead-market (DAM) settlement prices from 2011–2015 [94,95]. The variable operation and maintenance cost of the CCGT plant, $V_{O\&M}$, is 3.6 \$/MWh according to EIA [96]. All of the costs associated with operating an integrated CCGT-RO plant or standalone RO plant are included in the objective function defined by equation 3.8:

$$min \sum_{t \in T} \left[C_{power,j}(t) + C_{RO} \times V_{RO}(t) - R_{elec}(t)\right] \tag{3.8}$$

where the subscript j refers to either an integrated CCGT-RO (int) or standalone RO plant (s.a). This optimization model includes several constraints on the RO and CCGT plants. The the maximum hourly output constraint for the RO plant is defined by equation 3.9, and the minimum desalination output is defined as 40% of the maximum output as shown in equation 3.10 [97]:

$$V_{RO}(t) \leq x_{RO}(t) \times \dot{V}_{RO,max} \tag{3.9}$$

$$V_{RO}(t) \geq 0.4 \times x_{RO}(t) \times \dot{V}_{RO,max} \tag{3.10}$$

where x_{RO} is a binary variable that describes whether the RO plant is on or off. The minimum down time (DT) of the RO plant, set as five hours for this analysis, is defined by equations 3.11 and 3.12. The minimum annual capacity factor (CF) of the RO plant, set as 95% for this analysis, is defined by equation 3.13.

$$\begin{aligned} \sum_{n=k}^{k+DT-1} [1 - x_{RO}(n)] \geq DT[x_{RO}(k-1) - x_{RO}(k)] \\ \forall k = 1 \cdots T - DT + 1 \end{aligned} \tag{3.11}$$

$$\begin{aligned} \sum_{n=k}^{T} \{1 - x_{RO}(n) - [x_{RO}(k-1) - x_{RO}(k)]\} \geq 0 \\ \forall k = T - DT + 2 \cdots T \end{aligned} \tag{3.12}$$

$$\sum_{t \in T} V_{RO}(t) = \dot{V}_{RO,max} \times T \times CF \tag{3.13}$$

where T is the number of hours in a year. The RO plant integrated with a CCGT plant can only run when the CCGT plant is also running as shown in equation 3.14:

$$x_{RO} \leq x_{gen} \tag{3.14}$$

where x_{gen} is a binary variable that describes whether the CCGT plant is on or off. The maximum hourly electricity generation from the CCGT plant, W_{gen}, is defined by equation 3.15, and hourly electrical energy consumed by the RO plant, $W_{RO,int}$, is defined by equation 3.16.

$$W_{gen}(t) \leq x_{gen}(t) \times \dot{W}_{max} \tag{3.15}$$

$$W_{RO,int}(t) = V_{RO}(t) \times E_{RO} \tag{3.16}$$

Lastly, the hourly electricity generated has to be used to run the RO plant or sold to the grid as defined by equation 3.17.

$$W_{gen}(t) = W_{sell}(t) + W_{RO,int}(t) \tag{3.17}$$

This optimization analysis used fuel and electricity price data from 2011–2015 to determine whether the lower operating costs associated with generating electricity on site and the revenues associated with electricity sales are sufficient to justify the additional capital cost for integrating the CCGT plant with the RO plant. For a standalone RO plant, the amortized capital cost, $C_{cap,s.a.}$, is a function of the OCC of the RO plant, the annual capacity factor of the RO plant, and the capital recovery factor, CRF, as shown in equation 3.18.

$$C_{cap,s.a.} = \frac{OCC_{RO} \times CRF}{365 \times CF} \tag{3.18}$$

The OCC of the RO plant is defined as 1130 $\$/m^3$ per the cost estimating tool on Global Water Intelligence's `DesalData.com`. The CRF was calculated using equation 3.19 and assuming an interest rate, i, of 8% and a project lifetime, n, of 20 years. These values were chosen for illustrative purposes, and this analysis can be done using any values for the interest rate and project lifetime. A higher interest rate or lower project lifetime would increase the capital cost.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.19}$$

For the integrated CCGT-RO, the OCC and fixed operation and maintenance cost, $F_{O\&M}$, of the CCGT plant were normalized by the specific energy consumption of desalination to be in $/m^3 as shown in equations 3.20 and 3.21. The OCC of the CCGT plant is shown in Table 3.1. The fixed operation and maintenance cost for the CCGT plant is 13.2 $/kW-yr according to EIA [96]. The sum of amortized capital and fixed costs for the integrated CCGT-RO plant, $C_{cap,int}$, is shown in equation 3.22.

$$OCC_{CCGT,norm} = \frac{OCC_{CCGT} \times E_{RO}}{24\frac{hr}{d}} \tag{3.20}$$

$$F_{O\&M,norm} = \frac{F_{O\&M} \times E_{RO}}{24\frac{hr}{d}} \tag{3.21}$$

$$C_{cap,int} = \frac{(OCC_{RO} + OCC_{CCGT,norm}) \times CRF + F_{O\&M,norm}}{365 \times CF_{desal}} \tag{3.22}$$

The average cost of powering an integrated CCGT-RO or standalone RO plant, $\overline{C_{power,j}}$, is defined as the sum of hourly power costs divided by the sum of hourly desalination volume as shown in equation 3.23. Similarly, the average revenues earned from electricity sales for the integrated CCGT-RO plant, $\overline{R_{elec}}$, are defined as the sum of hourly electricity revenues divided by the sum of hourly desalination volume as shown in equation 3.24.

$$\overline{C_{power,j}} = \sum_{t \in T} C_{power,j}(t) / \sum_{t \in T} V_{RO}(t) \tag{3.23}$$

$$\overline{R_{elec}} = \sum_{t \in T} R_{elec}(t) / \sum_{t \in T} V_{RO}(t) \tag{3.24}$$

The LCOW is defined as the sum of the operating cost of the RO plant, the amortized capital cost, and the average cost of power minus the average revenues earned from electricity sales as shown in equation 3.25.

$$LCOW_j = C_{RO} + C_{cap,j} + \overline{C_{power,j}} - \overline{R_{elec}} \tag{3.25}$$

In summary, a simple Thermoflex model of a CCGT plant based on the power plant specifications (Table 3.1) and site conditions considered for this analysis was used to estimate the flow rate of water needed for the cooling system of a small-scale CCGT plant. This flow rate was compared with the total flow rate of seawater coming into the RO plant to determine if additional intake capacity would be needed for an integrated CCGT-RO plant. The carbon emission intensity of the CCGT plant was estimated based on the reported carbon emission intensity of natural gas and the efficiency of the CCGT plant as shown in equation 3.3. The carbon intensity of the CCGT plant was compared to the fleet average carbon intensity of the ERCOT power grid.

An optimization analysis was used to estimate the LCOW of an integrated CCGT-RO compared to a standalone RO plant. The decision variables used in this analysis include binary variables, x_{RO} and x_{gen}, that describe whether the RO plant and CCGT are on or off. The decision variables also include continuous variables for the hourly volume of water desalinated, V_{RO}, hourly electricity generation, W_{gen}, and the hourly electricity sold to the power grid, W_{sell}. Dependent variables include the hourly electricity consumed by the RO plant, W_{RO}, the hourly cost of powering the integrated CCGT-RO or standalone RO plant, C_{power}, and the hourly revenue earned from electricity sales, R_{elec}. These values, along with the operating costs associated with an RO plant and the amortized capital cost of an integrated CCGT-RO or standalone RO plant, were used to calculate the LCOW with equation 3.25.

3.3 Results

For small-scale CCGT plants ranging from approximately 36–71 MW, the cooling water flow rate ranges from 50.3 to 90.5 TCM/d, and the maximum desalination capacity ($\dot{V}_{RO,max}$) ranges from approximately 282 to 562 TCM/d (12-23 TCM/hr) as shown in Figure 3.2. For context, Sorek, the largest seawater RO plant in the world, has a capacity of 624 TCM/d [98]. Assuming a recovery ratio of 40–50%, the necessary flow rate of seawater intake would range from 565–1410 TCM/d. Thus, only 6–9% of the seawater intake for the RO plant would be needed to cool the power plant. The carbon intensity of the CCGT plant varies from 364–401 kg/MWh, 33–39% less than the average carbon intensity of 584 kg/MWhe kg/MWh for electricity purchased from ERCOT as shown in Figure 3.3. Electricity purchased from ERCOT has a higher carbon intensity because coal accounted for 27–36% of ERCOT's generation mix from 2011–2015 [91].

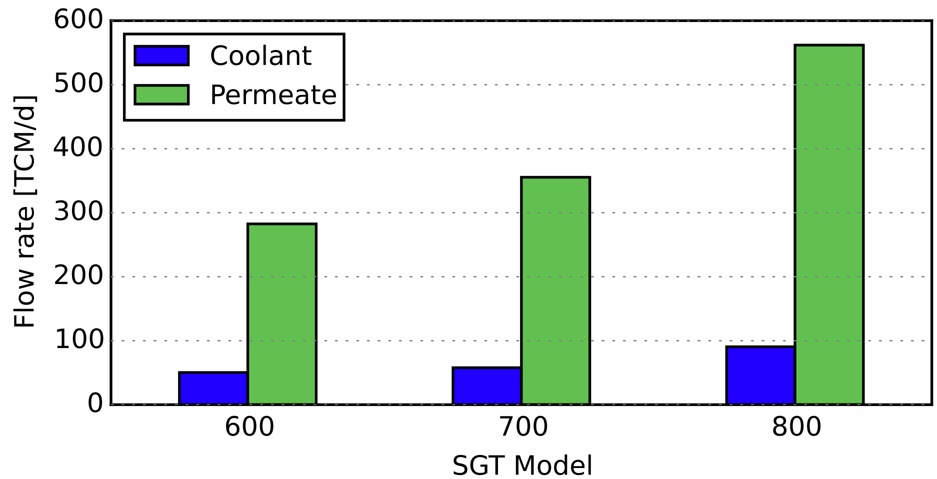

Figure 3.2: The flow rates [TCM/d] of power plant coolant are only 6–9% of the total flow rate of seawater intake for the RO plant assuming a 40–50% recovery ratio.

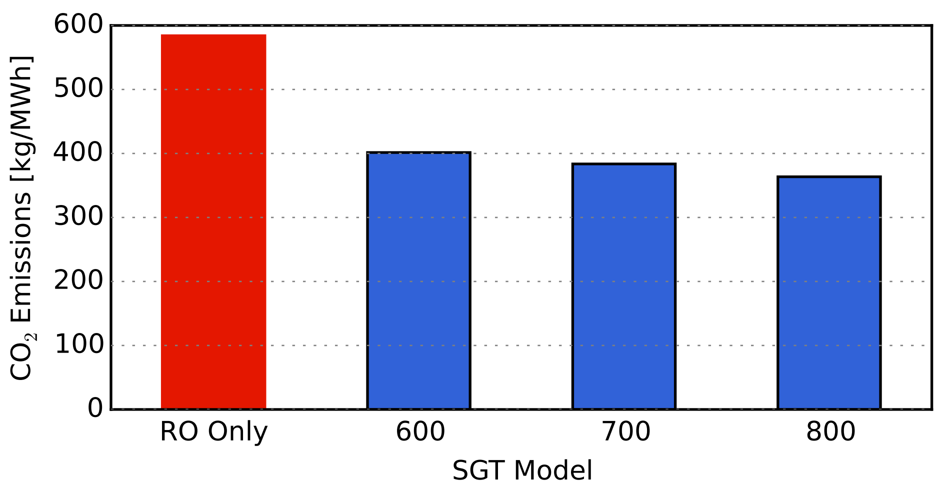

Figure 3.3: The average carbon intensity associated with electricity purchased from ERCOT is approximately 584 kg/MWh compared to 364–401 kg/MWh for a range of small-scale CCGT plants that could power an RO plant.

Compared to a standalone RO plant with the same desalination capacity, an integrated CCGT-RO has higher amortization costs but lower power costs. Subtracting the amortized capital cost of a standalone RO plant, equation 3.18, from the amortized capital cost of an integrated CCGT-RO plant, equation 3.22, the additional capital cost associated with the power plant is approximately 0.05 $\$/m^3$ as shown in Figure 3.4. From equation 3.23, the average cost of powering a standalone RO plant is approximately 0.18 $\$/m^3$ compared to 0.08–0.09 $\$/m^3$ for an integrated CCGT-RO plant as shown in Figure 3.5. An integrated CCGT-RO plant also earns approximately 0.02 $\$/m^3$ in revenues from electricity sales. From equation 3.25, the LCOW for a standalone RO plant is approximately 0.71 $\$/m^3$ compared to 0.64–0.65 $\$/m^3$ for an integrated RO plant, a decrease of 8–10%, as shown in Figure 3.6.As would be expected from the decreasing amortization and power costs in Figures 3.4 and 3.5, the LCOW tends to decrease when the RO plant is integrated with a bigger, more efficient CCGT plant.

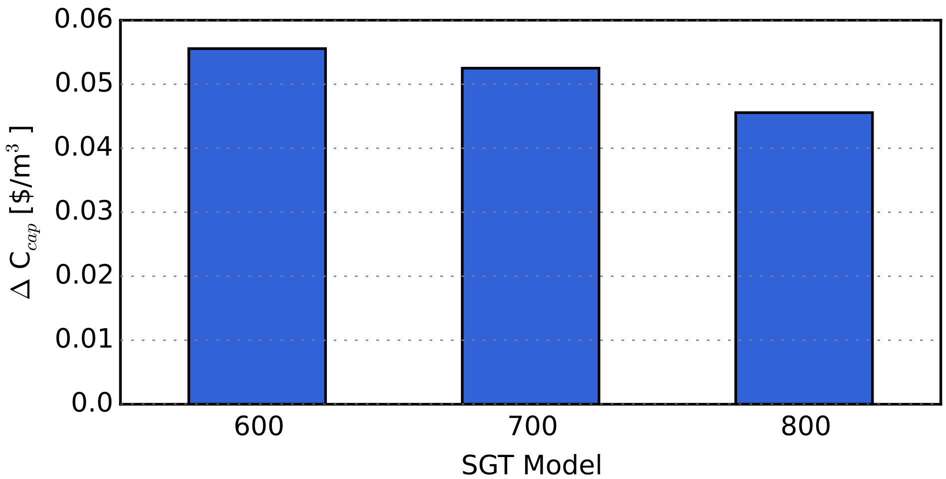

Figure 3.4: The additional capital cost associated with the power plant for the integrated CCGT-RO is approximately 0.05 \$/m^3.

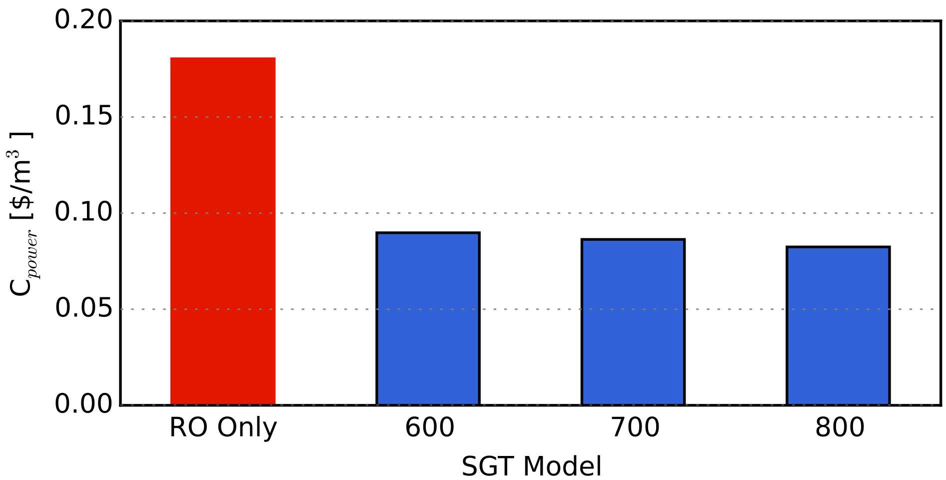

Figure 3.5: The power cost for a standalone RO plant is approximately 0.18 \$/m^3 compared to 0.08–0.09 \$/m^3 for an integrated CCGT-RO plant. An integrated CCGT-RO plant also earns approximately 0.02 \$/m^3 in revenues from electricity sales.

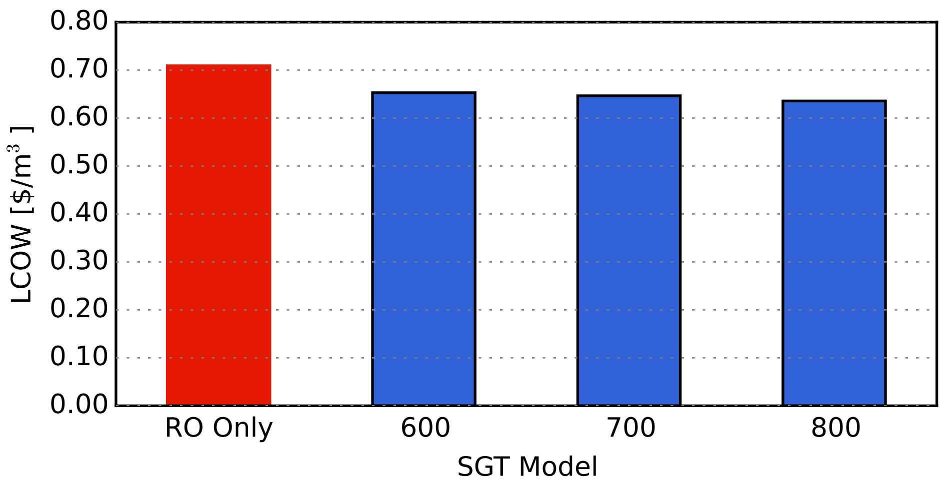

Figure 3.6: The LCOW for a standalone RO plant is approximately 0.71 $\$/\text{m}^3$ compared to 0.64–0.65 $\$/\text{m}^3$ for an integrated RO plant, a decrease of 8–10%.

3.4 Discussion

This study focused on the implications of integrating a seawater RO plant with a CCGT plant much smaller than what is typically built to be competitive in the electric power market. There were several motivations for considering such a small-scale CCGT plant. For example, even though it may make sense to integrate an RO plant with an existing large-scale power plant, it may not make as much sense to construct a new large-scale power plant just to power an RO plant. One dimension in which a small-scale CCGT plant might be preferable to a larger plant is that the cooling system of a small plant needs only a fraction of the total flow rate of seawater coming into the RO plant, and so no additional intake capacity is needed. A once-through cooling system for a 500 MW CCGT plant, on the other hand, would need an intake of more than 500 TCM/d, i.e., approximately 50% more than the intake for the Carlsbad RO plant outside San Diego, CA, the largest seawater desalination plant in the Western hemisphere [99].

Even though a small-scale CCGT plant is less efficient and has a higher overnight capital cost than a large-scale CCGT plant, an RO plant integrated with a small-scale CCGT plant still outperforms a standalone RO plant thermodynamically and economically. The carbon intensity of electricity produced by a small-scale CCGT plant is more than a third lower than the average carbon intensity of electricity on the ERCOT grid. However, ERCOT's carbon intensity is trending downward as wind, solar PV, and natural gas are replacing coal generation. Even so, the levelized cost analysis used in this study indicates that an RO plant integrated with a small-scale CCGT benefits enough from reduced energy costs and revenues from electricity sales to justify the capital and fixed costs associated with the CCGT plant.

This analysis assumed that the specific energy consumption of desalination was 3.05 kWh/m^3. This number is based on the most recently built large-scale desalination plants. As the specific energy consumption for seawater reverse osmosis decreases, the energy savings from integrating an RO plant with a small-scale CCGT plant decreases. For example, the Affordable Desalination Coalition has reported specific energy consumption as low as 1.74 kWh/m^3 for a demonstration project [86]. With such a low specific energy consumption, the energy savings from integrating an RO plant with a small-scale CCGT plant would be only 0.05–0.06 \$/m^3 instead of the 0.09–0.10 \$/m^3 energy savings reported in the results. Similarly, the energy savings would be higher than 0.09–0.10 \$/m^3 if the specific energy consumption was greater than 3.05 kWh/m^3.

The optimization analysis used to estimate the optimal hourly operation for an integrated CCGT-RO plant included an annual capacity factor constraint for the RO plant. A consequence of such a constraint is that the capacity factor of the RO can vary on a monthly basis, with the RO plant running less often in months with high wholesale electricity prices so as to maximize the revenues that can be earned from electricity sales. Averaging the optimal operating schedule of a CCGT-RO for the years 2011–2015 that were considered in this analysis, the capacity for the RO plant varies from as low as 86% in August to over 98% in months like November, December, and January as shown in Figure 3.7. These variations correspond to the monthly average wholesale electricity prices also shown in Figure 3.7. Note that the August prices are skewed by the extremely high prices from 2011 when the hourly average price was over 150 $/MWh. These results indicate that the owner of an integrated CCGT-RO plant would benefit from flexible purchase agreements that allow for some variation in monthly operation. Conversely, hot, dry months with high electricity prices may be coincident with high water demand or water scarcity. Customers for desalinated water might choose to have water purchase agreements that require the RO plant to produce a minimum amount of desalinated water on a monthly basis. Future research should consider how stricter constraints on the monthly or daily capacity factor for the RO plant would impact estimates for the revenues that can be earned from electricity sales.

Another way to manage the variability in monthly desalination output would be to invest in water storage capacity. For example, for a 300 TCM/d plant, a 10% difference in monthly output is a difference of approximately 90 thousand cubic meters. Future research should investigate the tradeoffs between monthly variability in desalination output and electricity sales versus the cost of water storage capacity.

When comparing the cost of an integrated CCGT-RO with that of a standalone RO plant, it is assumed that a standalone RO plant would have to purchase electricity from the grid or through a power purchase agreement at a

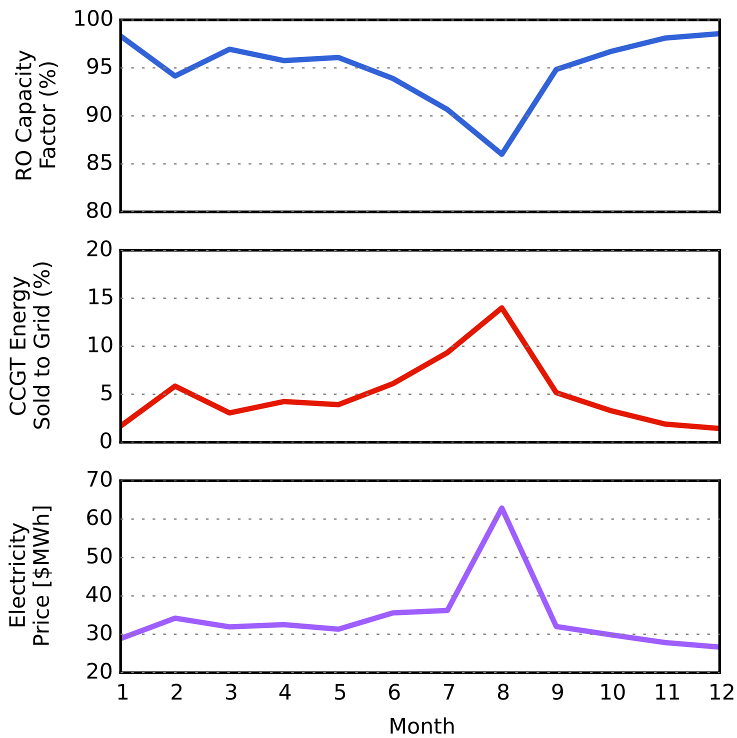

Figure 3.7: With an annual capacity factor constraint for the RO plant, operation of a CCGT- RO plant varies over the course of the year to maximize revenues earned from electricity sales.

fixed rate. If a standalone RO plant were instead allowed to purchase electricity at rates based on the time of use, it is conceivable that the average price of electricity could be cheaper if the RO plant is able to schedule its operation around peak electricity prices. It is also conceivable that time of use rates could be designed in such a way that there could be times of day or short-term market conditions when it would be cheaper to power an integrated CCGT-RO plant with electricity purchased from the grid rather than generating electricity on site. Future research should investigate how incorporating different time of use rates into this analysis would affect the results.

3.5 Conclusions

There are several benefits from integrating and powering an RO plant with a small-scale CCGT plant rather than purchasing electricity from the grid. With a small-scale CCGT plant, no additional intake capacity is needed for the power plant cooling system. In Texas, the carbon emission intensity for a small-scale CCGT plant is 33% lower than the average carbon intensity of electricity on the ERCOT power grid. From an economic standpoint, the cost of powering an integrated CCGT-RO is, on average, less than half the cost of powering a standalone RO plant with retail electricity. This reduction plus revenues earned from electricity sales are sufficient to justify the additional capital and fixed costs associated with the CCGT plant.

Chapter 4

Summary

4.1 Power Generation and Desalination Systems in Kuwait

A unit-commitment model of power generation and desalination plants in Kuwait was used to investigate strategies for reducing the cost and environmental impact of these systems. The first of these analyses sought to determine the optimal allocation of fuel among the power and desalination plants in Kuwait. In strict cost terms, gas oil should be used sparingly for power generation or desalination. Another result of this research was to determine whether certain plants should run more or less often relative to the historical data. This analysis indicates that some of the older cogeneration plants should be run sparingly, while the RO plants should be run as often as they are available.

This analysis was followed by a case study in which some of the plants were restricted to only burning natural gas to limit local emissions of SO_2 and NO_x. The results indicate that restricting the consumption of fuels other than natural gas at the Doha power plants would have significant emission reductions at Doha and noteworthy emissions reductions system wide. The cost of these reductions would be a modest increase in fuel and O&M cost as the result of shifting generation and desalination to other plants. Because more natural gas is consumed at Doha West, less is leftover for combined cycle natural gas plants that can't burn heavy fuel oil or crude oil. As a result, the output of less efficient steam turbine power plants increases in the case study, and the output of combined cycle plants decreases in the case study.

The second strategy evaluated the impact of adding solar PV and new RO capacity to Kuwait's existing power generation and desalination assets. The results indicate that building solar PV and new RO in Kuwait could reduce both cost and emissions. Reverse osmosis is less energy intensive than thermal distillation, and building new RO capacity has the effect of reducing reliance on cogeneration plants to distill water. As a result, the output of cogeneration plants can be decreased in favor of more efficient combined cycle power plants or solar PV. Savings from solar PV decrease after 8 GW of new capacity because curtailment of solar energy increases significantly. However, for as many as three new 30 MGD RO plant, system-wide savings increase by approximately 3% with each new plant.

The last strategy considered the impact of implementing a tax on CO_2 emissions from power and desalination plants. The main effect of a CO_2 tax is to reduce the consumption of crude oil in favor of LNG as the carbon tax exceeds 40 USD/ton. A CO_2 tax also has an effect on power plant dispatch, with power-only plants, mostly combined cycle natural gas plants, running relatively more often and cogeneration plants running relatively less often. A CO_2 tax above 40 USD/ton has the effect of reducing emissions of CO_2, SO_2, and NO_x. The biggest impact on emissions is on SO_2, which decreases by 29% with a 100 USD/ton tax on CO_2 compared to a 5% or 6% reduction in emissions of CO_2 and NO_x, respectively.

4.2 Systems-Level Thermodynamic and Economic Analysis of a Seawater Reverse Osmosis Desalination Plant Integrated with a Combined Cycle Power Plant

There are several benefits from integrating and powering an RO plant with a small-scale CCGT plant rather than purchasing electricity from the grid. A small-scale CCGT plant requires no additional intake capacity for the power plant cooling system. In Texas, the carbon emission intensity for a small-scale CCGT plant is more than 33% lower than the average carbon intensity of electricity on the ERCOT power grid. From an economic standpoint, the csost of powering an integrated CCGT-RO is, on average, less than half the cost of powering a standalone RO plant with retail electricity. This reduction plus revenues earned from electricity sales are sufficient to justify the additional capital and fixed costs associated with the CCGT plant.

4.3 Conclusions

This manuscript adds to the body of work on the energy-water nexus with an emphasis on the interactions between power generation and desalination systems. Several general conclusions can be draws from these analyses. In countries like Kuwait where a significant percentage of freshwater is produced with desalination, demand for desalinated water has important implications for the operation of the power system. Reliance on cogeneration power plants and thermal distillation can limit the extent to which a power system can take advantage of more efficient combined cycle power plants or renewable energy sources like solar PV or wind. Thus, future investments in desalination capacity should use RO to limit energy consumption and maintain power system flexibility.

The systems-level analysis of an RO plant integrated with a small-scale power plant in Texas indicates that there can be substantial economic and environmental benefits to integrating a desalination plant with a power plant if the emission intensity and operating cost of the on-site power plant is less than purchasing electricity from the grid. Such an arrangement could incorporate a variety of power generation technologies not considered in this text, including reciprocating engines, small modular nuclear reactors, variable renewable energy sources like wind and solar, battery storage, and combinations thereof. The potential benefits of having an on-site source of electricity is likely to change over time, as the grid is decarbonized and the marginal cost of electricity decreases.

Appendix

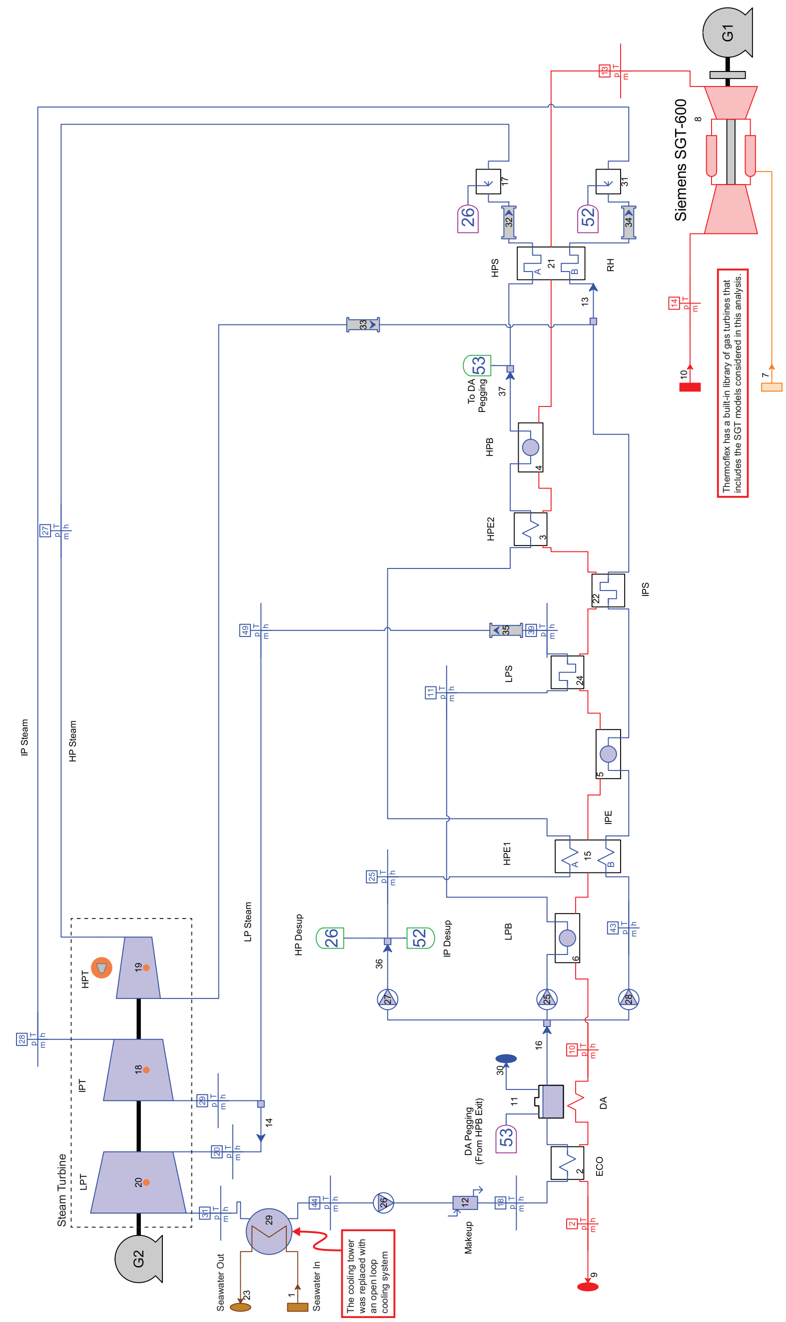

Figure 1: A sample CCGT model included with Thermoflex was used to estimate the coolant flow rate for a CCGT plant. This model was modified to have an open loop cooling system and the SGT models (600, 700, 800) described in the paper.

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